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The role of window glazing on daylighting and energy saving in buildings

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ABSTRACT

Energy conservation in building arena is essential issue for achieving sustainable environment. However, buildings experienced significant amount of heat gain or loss through window and this will affect the thermal comfort of buildings' occupants. Building without window is able to save energy, but it is not recommended due to the benefits of natural light on visual comfort and the biological effect of natural light on humans. Hence, window design plays important role in building architect. One of the essential parts of window is the glazing. Selecting a window glazing is complicated when energy saving and daylighting aspects of a building are considered concurrently. Optimization techniques offer a balance solution for the contradictions in selecting a window glazing of energy-efficient building. This paper intended to reveal the impacts of window glazing on the energy and daylighting performances of building through the previous researches. Then, the optimization techniques used by various researchers in choosing a glazing are highlighted. The emerging glazing technologies were discussed as well.

Contents

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1. Introduction

Despite promising premises, renewable energy systems are not infallible, which is primarily why the progress in the employment of renewable power generation is rather sluggish. This trend is highlighted in a report by Jäger-Waldau and Ossenbrink [1]; positing the fact that the European Union stops short of completely exploiting the sources of renewable energy that are available to them. Moreover, Paço and Varejão [2] posited that there are some obstacles preventing the full implementation of renewable energy resources, especially with regards to policies. Besides, the IEA [3], in the World Energy Outlook 2012, found that even though the new development and policies planned by many nations are being accounted for, the global community still fall short of charting a sustainable path in the context of a global energy system. Due to the numerous shortcomings and obstacles towards a full implementation of renewable energy, energy savings are crucial towards realising sustainable development.

Energy saving especially in buildings are worthy of our attention; Pérez-Lombard et al. [4] stated that the energy consumption by both residential and commercial buildings in developed countries account for 20–40% of total energy used. Those energies are mainly used for space heating and cooling (for residential buildings) and lighting (for commercial buildings) [5]. The energy performance of a building is depending on the building envelop especially the window. Lee et al. [5] reported a finding of Bülow-Hübe [6]: window responsible for 20–40% wasted energy in a building. In order to limit the heat gain or heat loss, building's window shall put in minimum size. However, the nature of a window is to allow the penetration of natural light into buildings. Moreover, the biological benefits of natural lightings and exterior view has been confirmed by researches [7–10]. Thus, fenestration design need proper planning in order to fulfil its nature of providing natural lighting and external view while keeping a balance energy performance of building.

Window glazing selection is one of the crucial issues in designing window. Previously, researchers had done the literature review in window glazing to provide the overview of various glazing. For instant, Arasteh [11] conducted a literature review on the advances in window technology within the year of 1973–1993. In his research, he mentioned the potential energy saving from windows, discussed the mechanism of heat transfer via windows, and the development of technologies helping windows reduce heat losses. He mostly focus on the development of glazing, started from low-emissivity coatings and low-conductivity gas fill glass, to a more advanced glazing such as evacuated window, transparent insulating materials (TIMs) and switchable glazing technologies, which were still under development at the time.

Moreover, Baetens et al. [12] conducted a literature research that focus upon smart windows in order to achieve dynamic daylight and solar energy control in buildings. The paper reviewed quite a number of technologies, such as transparent conductors and electrochromic windows, based on different metal oxides as well as polymers. Gasochromic devices, liquid crystal devices, and electrophoretic or suspended-particle devices were also included in the discussion. They seem to conclude that electrochromic windows are the most promising technology vis-à-vis daylight and solar energy purposes. The reliability of windows that are commercially available has been proven to be viable, with their tested properties falling within our expectations. These windows reduces almost 26% of lighting energy compared to well-turned daylighting control via blinds, and around 20% of the peak cooling loads in warmer climates, such as California (USA). This is however, not definitive for cooler climates, which requires further investigations for confirmation in this context. Lampert [13] also did a compilation of information regarding the optical switching technology – chromogenic materials for glazings. The author focused the discussion on the technical issues of the optical switching technology and touched some energy and daylighting issues using those glazing.

Jelle et al. [14] conducted a state-of-the-art review on high performances fenestration products, ranging from glazing to spacers, frames etc. The research team also include the rooms for future research opportunities in the fenestration field. This review paper presented the list of manufacturer specifications of various fenestration products as well.

From the literature survey, the previous review papers regarding the window glazing are mainly focused on advances of the window glazing technologies. Besides, some review papers also provided the technical issues, uses of the glazing and manufacturer specifications of various glazing technologies. However, the issues concerning how far or how much the glazing technology can help in energy saving and daylighting are seldom appear in the previous review papers. Selecting a window glazing become complicated when daylighting and energy saving need to be considered simultaneously. There are plenty of case studies conducted to verify or quantify the scientific specifications of the window glazing in realising the daylighting and energy saving in building. Besides, researchers had putting their effort in optimising the visual and energy aspects of window glazing. But, compilations of information of those case studies are still a missing link in the literature. Hence, this paper intended to review the information regarding selecting a window glazing for optimum daylighting and energy saving in a building through the case studies done previously. This literature research first reveals the impact of various window glazing on the visual and energy aspects on the

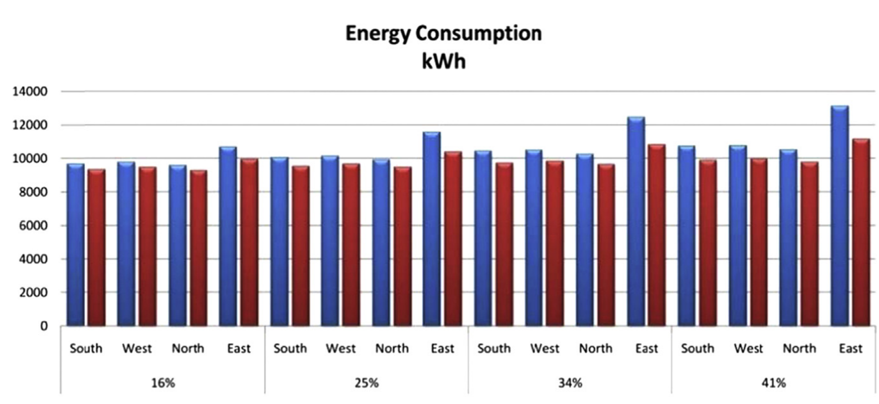

Fig. 1. Annual energy consumption for ARGON filled windows with different window-to-floor ratios (blue bar – double glazed window, red bar – triple glazed window) [15] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

building. Then, optimization techniques of researchers are presented.

2. Static window glazing

Static glazing refer to glazing that possesses single fixed optical and thermal properties, such as *U*-value, visible transmittance (Tvis), or solar heat gain coefficient (SHGC). This section presents how optical and thermal properties of static glazing affect the heating and cooling performances of a building. This section will review the impact of static window glazing on the thermal, daylighting and energy performance in buildings.

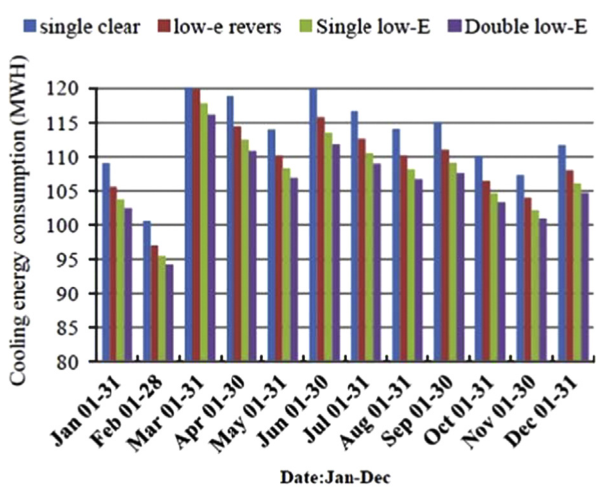

Fig. 2. Comparison of cooling energy used for different glazing [18].

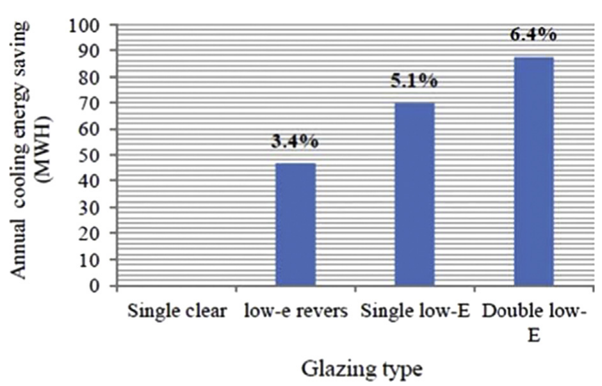

Fig. 3. Saving in annual cooling energy of advanced glazing compared to single clear glazing [18].

2.1. Effect of static glazing properties on thermal energy performance of building

Shakouri et al. [15] compared the thermal performance of double-glazed and triple-glazed windows. Different window sizes and orientations were taken into account in his study as well. The energy consumption for the double-glazed and triple-glazed windows with different sizes and orientations were plotted in Fig. 1.

The annual energy consumption for the double-glazed window was always higher than that of triple-glazed window, irrespective of orientations and window-to-floor ratios. This result highlighted the fact that double glazed fenestration systems allowed more gain in the solar heat compared to a triple-glazed window. Also, a triple-glazed system reduces the thermal transmittance of the windows, due to its additional insulation, making it more advanced in the context of thermal performance. Another factor that makes three-layer glazed superior was its thickness; thermal conductivity of the window drops as the window layers increases.

Sadrzadehrafiei et al. [16] had also conducted an examination on triple-glazing and its benefits towards cooling energy in tropical climates such as Malaysia. The study compared the cooling energy savings that could be achieved by single clear glass and triple glazing. Moreover, the study also compared the performances of two triple-glazing with 15 mm and 16 mm air gap between them. Results of the study showed that triple-glazing was able to achieve cooling electricity savings of 6.3%, compared to a single clear glass. The savings by using a 16 mm air gap triple-glazing is more than that in the 15 mm, but the difference was insignificant.

“Cooler” daylight is transmitted by the low emissivity glazings as compared to other types. This is because a higher amount of solar infrared radiations are reflected by the low E-glazings for a certain visible transmittance. The energy use effects of low-E glazings in comparison to the conventional glazings at various window-to-wall ratios were studied by Sweitzer et al. [17] with respect to the cooling, lighting and energy conservation in daylight office buildings. Savings in lighting, cooling and energy were obtained in both hot and cold climates by the insulated glazings with low-E coatings. The mean radiant temperature of the interior environments was also increased in the winter and was reduced in the summer. In addition it provided flexibility in terms of architectural design without any worries of unpleasant effects. The increase in the glazing luminous efficacy constant (k_v) within the range of 0.5–1.0 led to significant lighting, cooling and total electricity savings, while savings were reduced in the case of a constant exceeding 1.0 ($k_{v,s}$). Major advantages are received for cold climates when the *R*-value with glass units having a low *E* were used in larger numbers, but this may not be the case in hot climates. The energy savings achieved through small cooling equipment will be enough to cover the high installation costs. In

Table 1
Glazing descriptions [19].

Choices	Descriptions
(i) Single pane clear glass	3 mm clear glass
(ii) Type A	Insulating glass unit composed of: outer pane: 6 mm clear glass, air space: 12 mm, inner pane: 6 mm clear glass
(iii) Type B	Insulating Glass unit composed of: outer pane: 6 mm clear glass, air space: 12 mm, inner pane: 6 mm clear low-E (Pilkington)
(iv) Type C	Insulating glass unit composed of: outer pane: 6 mm silverstar sunstop neutral 50 (glastroesch), air space: 12 mm, inner pane 6 mm clear glass
(v) Type D	Insulating glass unit composed of: outer pane: 6 mm solar E glass (Lkington), air space: 12 mm, inner pane: 6 mm clear glass
(vi) Type E	Insulating glass unit composed of: outer pane: 6 mm blue tinted (Visteon), air space: 12 mm, inner pane: 6 mm clear glass, inner pane: 6 mm clear glass
(vii) Type F	Insulating glass unit composed of: outer pane: 6 mm bronze tinted (Glaverbel), air space: 12 mm, inner pane: 6 mm clear glass
(viii) Type G	Insulating glass unit composed of: outer pane: 6 mm grey tinted (glaverbel), air space: 12 mm, inner pane: 6 mm clear glass

addition, saving costs on high demands, profits in the long run from improved rentals, and more productivity owing to the occupant's comfort level enhancing may balance the high initial cost of installation of these glazings.

Sadrzadehrafiei et al. [18] had examined the effect of certain glazing, such as single clear glazing, single low emissivity (low-e) glazing, and double low-e glazing on the cooling consumption of the Chancellery office building, Universiti Kebangsaan Malaysia. The building was originally installed with the single clear glazing, and its cooling performance was compared with advanced glazing; single low-e pane, single low-e reverse pane, and double low-e pane, which included a clear pane and a low-e glazing, separated by a layer of air. Figs. 2 and 3 Compare the effect of different glazing types on energy consumption of cooling and annual energy saving in cooling respectively. The advanced glazing leads to cooling energy savings of the building, ranging from 3.4% to 6.4%. Among the advanced glazing, double low-e pane yielded the highest energy savings compared to the other glazing.

Hassouneh et al. [19] investigated the influence of glazing types and orientation on energy balance of apartments in Amman, Jordan. This research is intended to discover the suitable glazing and its area for four main orientations from eight choices of glazing. Brief descriptions of glazing were tabulated in Table 1.

Table 2
Thermal charecteristic of windows [20].

	Single glazed	Double glazed L	Double glazed H	Triple glazed
U-value	5.68	2.83	1.4	0.68
SHCG	0.855	0.775	0.589	0.407
Rf-sol	0.075	0.126	0.266	0.231
T-vis	0.901	0.817	0.706	0.625
Gas fill	–	Air	Argon	Krypton

The results showed that different types of glazing performed differently in different directions. Clear glass was effective in the South, East and West directions, but not in the North. In the Northern direction, the energy losses exceeded the energy savings, thus it holds negative percentages of energy savings. Compared to clear glass, Type A glazing contributed energy savings in all directions, especially in the South, East and West. The percentages of energy savings for Type-A glazing are higher than those for clear glass, for instance, in the South direction, Type-A glazing was able to achieve energy savings three times more than that of clear glass. Furthermore, Type-A had little effect on elevating energy savings in the Northern orientation.

In the Northern direction, most of the glasses caused energy losses instead of energy savings. However, Type-B glazing had showed that it is able to achieve positive energy savings when the glass area is large enough. Therefore, in the city of Amman, Jordan, Northern orientated window should be avoided. Nevertheless, if it is unavoidable, then the Type-B glazing is the best option for Northern windows. In the southern direction, larger glazing area helps reduce the heating energy during winter, depending on the glazing type. Overall, all types of glazing performed better than clear glass. They mostly performed very well in the South, East and West directions, with different percentages of energy savings. The glazing Types E, F and G resulted in similar amounts of energy savings in all directions, and their energy savings are about double that of clear glass. From this study, the authors revealed that there is certain glazing types that performed more efficiently in a specific direction, which makes choosing the glazing type paramount towards energy savings.

Jaber and Ajib [20] investigated the optimum window type and size for both heating and cooling demands in three different climate zones – Amman, Aqaba and Berlin. The thermal characteristics of different types of windows were described in Table 2. Note

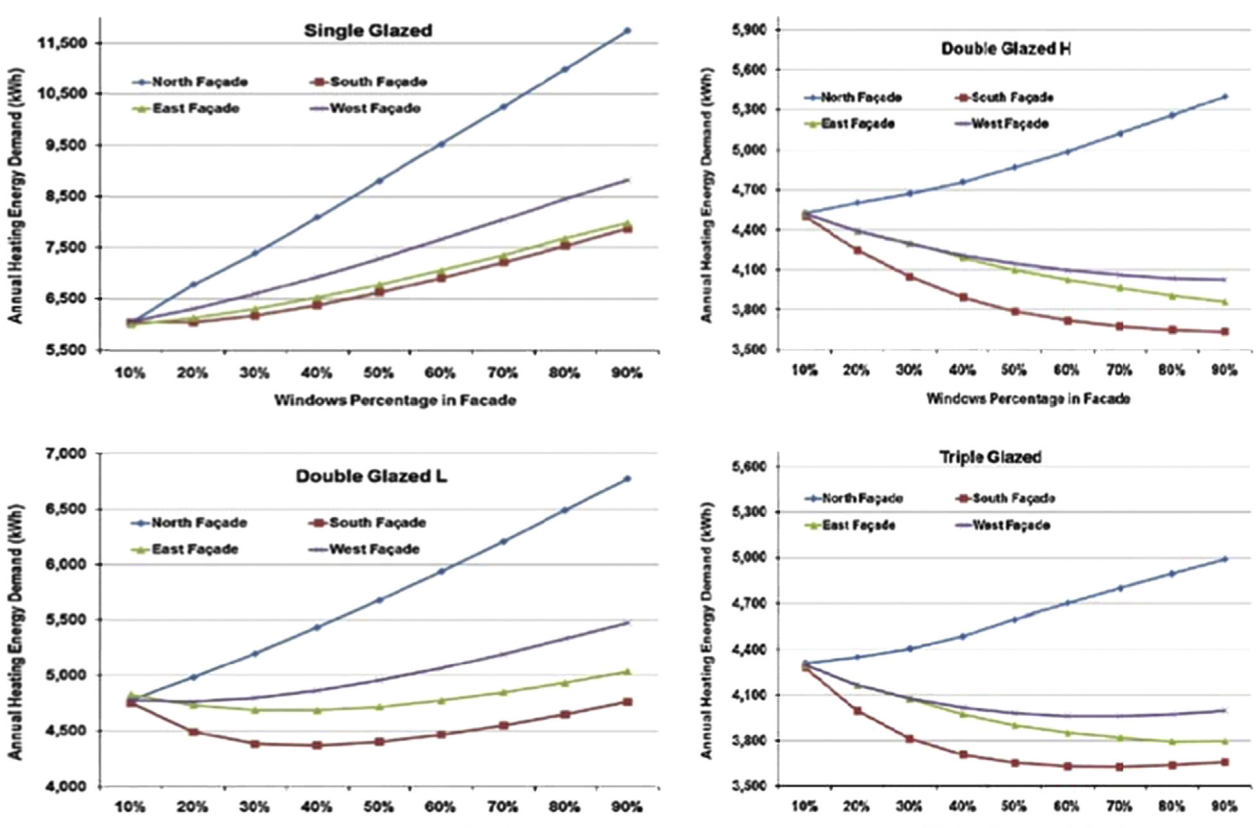

Fig. 4. Effect of window glazing on annual heating load in Amman as a function of window sizing [20].

Table 3
Daylight factor (DF) distribution for clear glass [21].

distance from window	25wwr	35wwr	45wwr	55wwr	65wwr
0.25	22.4	25	27.2	31.6	35.4
0.75	11.3	15.7	19	21.2	24.5
1.25	6.6	10	13.5	16.8	18.5
1.75	4.4	6.8	9.5	12.2	14.3
2.25	3.4	5.1	7.5	9.7	11.6
2.75	2.7	4.5	6.3	8.3	9.8
3.25	2.4	3.9	5.6	7.3	8.8
3.75	2.5	3.7	5.5	7.1	8.5
4.25	1.4	2.2	3	3.8	4.5
%of daylit floor area	*57*	*70*	*90*	*90*	*90*
% sup light needed	*43*	*30*	*10*	*10*	*10*

Key:

- >10 DF: adequate to overlit
- < 10 DF, > 5DF: good quality daylight
- < 5 DF, >2 DF: require light
- < 2 DF: require full artificial light

Table 4
Parameters of case studies [22].

Parameters	Case study 1	Case study 2	Case study 3
Window type	Casement window	Fixed louver window	Adjusted louver window
Window head height above the floor surface	2170 mm	2325 mm	2170 mm
Glass type	Obscure glass	Clear glass	Tinted glass
Thickness of the glass	3 mm	3 mm	3 mm
Visible transmittance (Tvis)	0.18	0.64	0.56
Solar heat gain coefficient (SHGC)	0.57	0.63	0.65
U-value	0.90	0.90	1.25
Size of the window	$1830 \times 1250\ mm^2$	$1227 \times 625\ mm^2$	$1830 \times 1250\ mm^2$

that SHCG is solar heat gain factor, Rf-sol is solar reflectance of outer surface of glazing systems, and T-vis is the visible transmittance of the window.

The results showed that as the *U*-value decreases, the annual heating energy for all sites decreases. Also, the highest heating demand occurred at the Northern façade at all sites, as it received a low solar incident radiation. On the other hand, the Southern façade induced the lowest heating energy; due to being the recipient of high solar incident radiations. Fig. 4 shows the effect of glazing at Amman; the other two locations displaying similar trends with Amman. The lower the *U*-value of glazing implies a lesser glazing conduct energy from the outside into the building. Therefore, the window with a lower *U*-value helps maintain the space's temperature by reducing the conduction of heat from the exterior to the interior.

The study also revealed that the annual cooling energy slightly decreases as the *U*-value of glazing drops for all sites. The orientations that induced the highest cooling load were different: in Amman, the highest cooling load occurs at the East façade, while in Aqaba and Berlin, it occurs at the West façade. However, orientations that required the least cooling demand are the same for all locations and all types of glazing, which is the Southern façade.

2.2. Effect of static glazing properties on daylighting level of the building

This section revealed the impact of static daylighting opportunities of a building. The daylight penetration heavily depends on the Tvis of the static glazing. Ibrahim and Zain-Ahmed [21] investigated the daylight availability in Malaysia's office interior by varying different type of window glasses; clear glass, tinted green glass, and reflective glass with visible transmittance (Tvis) value of 88%, 75% and 30%, respectively. Table 3 shows the daylight availability of clear glass in different depths, window sizes and percentage of daylit floor area. As shown in the results, clear glass allow the usable daylight ($DF > 2$) to penetrate 3.75 m into room depth, even with the smallest opening of 25WWR. Full daylight environment ($DF > 5$) can be experienced up till 3.75 m deep, with a minimum 40–45WWR.

However, changing the clear glass to tinted green glass reduces the chances for daylighting the space. The usable daylight ($DF > 2$) had to be achieved with a minimum of 40WWR, whereby the $DF > 5$ (fully daylit) needed a minimum opening of 55WWR. Reflective glass will provide a minuscule of chance of daylighting the space; only a maximum of 1.25 m room depth was able to experience a fully daylit environment ($DF > 5$). This study had shown that as the Tvis value decreases, the opportunity for the space to utilise daylight decreases as well.

Syed Husin and Hanur Harith [22] examined the typical windows in Malaysia, such as the casement windows and louver windows in the context of their ability to distribute daylight into space. This study included three case studies using different glass types, as summarized in Table 4.

All the case studies were conducted in the selected houses that were in the same area, and they all tend to receive maximum daylight during 9.00 am compared to 5 pm. For all the case studies, daylight transmittance was higher at the area nearer to the windows. In case study 1, the obscure glass allowed the highest daylight level to penetrate into space at 9.00 am. Then, the daylight level drops at 12 o'clock noon and 5.00 pm. Even though there were drops in daylight level throughout daytime, the casement window with obscure glass still provided enough daylight to the occupants for them to carry out their general tasks within the range of 4 m from the windows.

The windows in case study 2 was positioned at a higher level compared to the other two. The intention was to allow more daylight penetration, as it was assumed that higher windows result in deeper daylight penetrations. However, the window size in this case study was relatively small compared to the other two windows. Daylight distributed by this window was inadequate to daylit the space, and it requires assistance from artificial lighting. Hence, this case study revealed two important consequences: (1) windows with small sizes will not allow deep daylight penetration, even though the window is positioned at a higher height. (2) Clear glass is supposed to be able to transmit 64% of visible light into the space (Tvis=0.64), but the window's size influences the performances of clear glazing.

Case study 3 recorded the highest daylight level at the point of 1 m from the window. This is due to the window's ability to admit 56% daylight, at the same time limiting the glare and redirect the diffuse daylight. Also, this kind of glazing allows sufficient daylight up to the range of 3 m from the window. This research concludes that in Malaysia, typical glazing generally allows good quality daylight penetration. Nevertheless, window sizing and positioning played equally important roles in affecting the window's performances.

Various types of glazings were analysed by Taylor et al. [23] to gain optimum levels of natural light. This study also included the clear glass for small office buildings, which were to be constructed in Canberra, Australia. A client wanted to optimize the glazing with respect to the greenhouse gas emissions and thus asked to perform the thermal modelling. A daylight model was obtained through the thermal modelling that was not applicable at that time. But this model was developed to study the effects of glazings chosen for natural lighting as well as the inclusion of light shelves as an alternative to tinted glass for solar control.

2.3. Effect of static glazing and climate background on total energy performances of building

The total energy refers to thermal and lighting energies. The lighting energy was very dependent on the daylight performances of the building. Moreover, the background was closely related to the location of the sites. This section discussed the effect of static glazing and site location on the total energy performances of the building.

Johnson et al. [24] investigated the influence of glazing systems on component loads and annual energy use in prototypical office buildings with using a simulation programme and described the sensitivity of total energy use to orientation, window area, glazing properties (*U*-value, shading coefficient, visible transmittance), window management strategy, installed lighting power, and lighting control strategy. All three cases (opaque wall, nondaylighted building, and daylighted building) were examined and compared. The results indicated that the effective use of daylight and lighting controls will produce large reductions in electric lighting energy consumption. The increasing of window area and/or transmittance to increase daylighting savings frequently reaches a point, depending on climate and orientation, beyond which total energy consumption increases due to greater cooling loads.

Stegou-Sagia et al. [25] inspected the effect of static glazing on the energy breakdown for office buildings in Greece. The variables include glazing type and it sizes and the effect of climate, since the study includes two cities in Greece with different climate backgrounds. Office building was first simulated with double-glazed grey tinted windows, with the size of 20% of the total wall area. Then, the double-glazed grey tinted windows were substituted by double-glazed clear glazing. The simulation is then continued with smaller size of 10% of total wall area, and another climate background.

Table 5
Total annual energy consumption for office in Athens and Thessalonica [25].

Type of glazing: double	Total annual energy consumption (MJ/m^2)	
	Athens	Thessalonica
Grey tinted (20% of wall area)	1714.5	1741.8
Clear glass (20% of wall area)	1894.0	1863.9
Reduced glazing area (10% of wall area)	1613.5	1615.7

The results proved the fact that climates are not influential vis-à-vis annual energy consumption (Table 5). Even so, the energy breakdowns were different for the two cities. More space heating is needed by Thessalonica, as it has lower winter temperatures (Fig. 5). The annual energy consumption is lowest with reduced glazing area, but adversely affects visual aspects. Therefore, grey tinted double glazing offers more balance solutions to office building.

Lee et al. [5] investigated various window systems in order to determine the optimized window for five distinctive Asian climates (Manila, Taipei, Shanghai, Seoul and Sapporo). Other than window sizes and orientations, this study revealed the influences of *U*-value, SHGC, and Tvis on the energy and visual aspects of the buildings, based on different climates. Generally, lower *U*-value is more beneficial in reducing the heat conduction of the outside-to-inside of space. Lee et al. [5] came up with similar results as other researchers (Fig. 6). However, they found that the *U*-value influences reduction in the heating load more than the cooling load; this is agreed upon by Jaber and Ajib [26]. From the results, the reduction in cooling load is highest in Manila (7%), and lowest in Sapporo (0.7%). On the other hand, the heating load is reduced to as high as 49% in Shanghai, and as low as 37% in Sapporo. Therefore, *U*-value is more influential vis-à-vis heating load compared to cooling load, and it is suggested that in regions that require heating, the adoption of low *U*-value glazing is more advantageous.

SHGC value is always found to contradict heating and cooling seasons. Fortunately, the gap of heating and cooling demands for the five cities was insignificant. Hence, the results indicated that the lower SHGC benefits both heating and cooling demand in these five different climate regions. Tvis is important in influencing the use of artificial lights. For the regions in this study, all of them recorded that the usage of electrical lighting decreases logarithmically as the effective aperture (Tvis $\times$ WWR) increases.

Alrubaih [27] investigated the effect of four different static glazing types, such as the single clear, double clear, double low-e clear, and double reflect clear on energy savings and daylighting quality of sawtooth toplighting system under the principle orientations. The toplighting-to-floor ratio (TFR) is assumed 10%. The study was carried out using an existing single story academic university hall of UKM, Malaysia. The investigation is conducted using the OpenStudio-7 energy simulation programme supported by the EnergyPlus-7 calculation engine. The illuminanace level target of 500 lux for internal lighting was assumed. As shown in Table 6 and Fig. 7, the performance of glazing types is quantified and ranked based on high daylighting energy saving. High daylighting energy saving is determined by maximum total energy saving, and maximum cooling energy saving concurrently. The best performance of glazing types is found for double low-e clear. The results showed that the optimal lighting energy saving on the North, South, East and West orientations are 56.6%, 56.6%, 56.1%, and 55.8% respectively; the maximum total energy savings are 15%, 15.6%, 14.7% and 15.1% respectively; and the optimal cooling energy savings are 3.4%, 4.3%, 3.2% and 3.9% respectively. Double clear and single clear showed the second and third best performance, while double reflect clear showed the lowest performance.

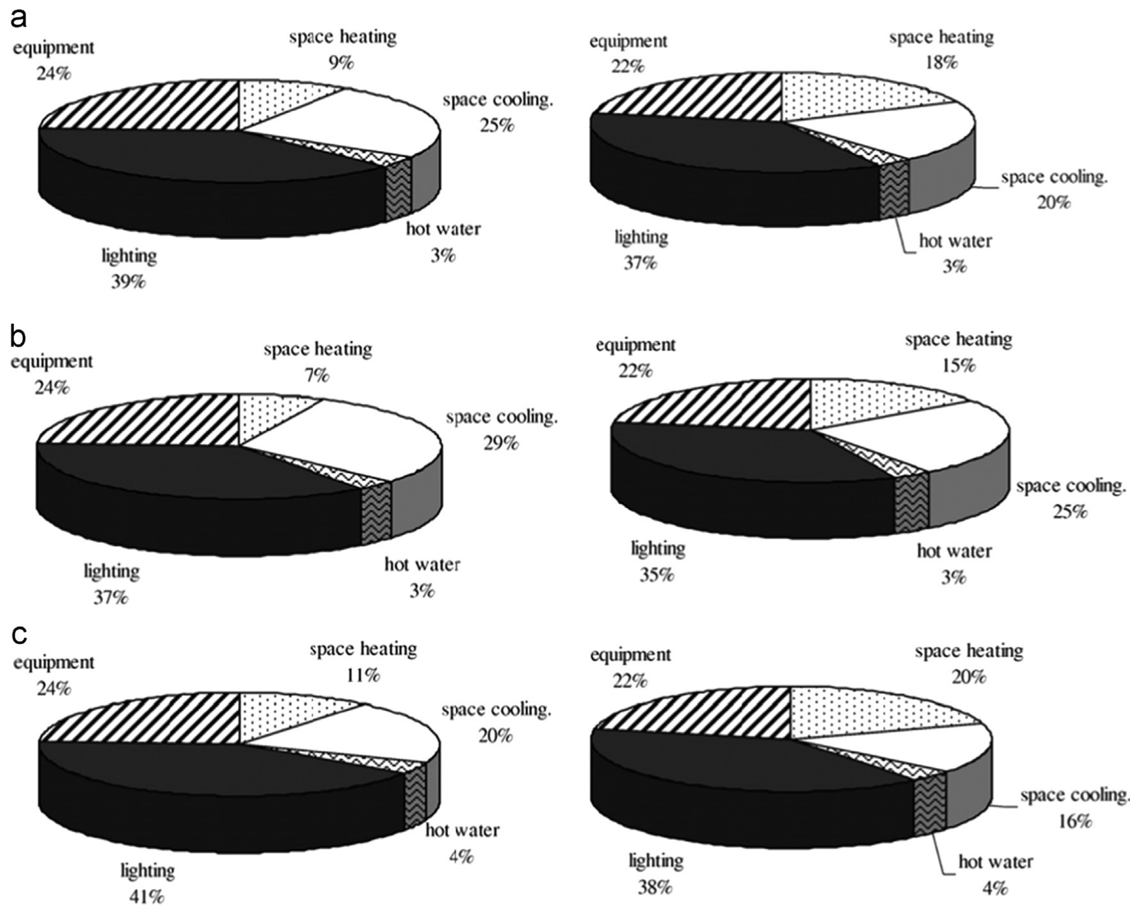

Fig. 5. Breakdown to end uses for the office building in Athens (left) and Thessalonica (right) for (a) double, grey tinted glazing, (b) double, clear glazing and (c) reduced glazing area to 10% of wall area [25].

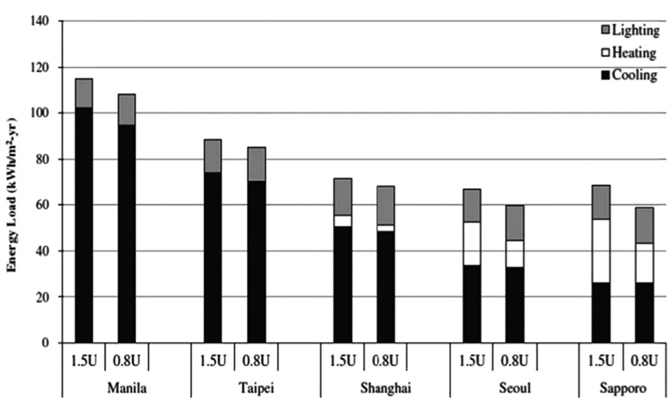

Fig. 6. Effect of *U*-value on building energy consumption in five Asia cities [5].

2.4. Technology and cost optimization for static glazing

Lee et al. [5] presented an optimization of window systems for the building's annual heating, cooling and lighting energy consumption in the Asian region. Manila, Taipei, Shanghai, Seoul and Sapporo were Asian cities that were chosen based on the five typical Asian climates. Triple-glazed and double-glazed glass, with a variety of window sizes, orientations, SHGC, Tvis and *U*-factor were taken into consideration. After a series of optimization processes, the window that is most efficient is showed in Table 7. Results showed that different climate backgrounds will yield different windows system. Also, with the exception of the most efficient window, the authors of this study also mentioned some others choices in case where there are obstacles that disallow designers to select the best windows.

In regions heavily dependent on cooling energy such as Manila and Taipei, North windows help increase energy savings due to its relatively low solar heat gain. Cities such as Shanghai, Seoul and Sapporo, which require heating energy at certain times of the year; the South window helps retain solar heat during the cold days. However, in order to limit the heat gains during the hot days, the South window has to be installed in smaller sizes compared to the North window. According to statistical study of [5], they found that the North window is less affected by WWR, SHGC and Tvis, compared to East and West mounted window. This indicates that if there is a necessity for East and West window, heavy consideration on glazing properties are needed.

Hassouneh et al. [19] stated that the best type of window from an energy standpoint must: (1) save energy, (2) reduces heat loss, (3) save money, and (4) low cost. Therefore, after a series of investigation of glazing properties (based on Table 1 and Section 2.1), the team did an economic optimization for designers in the context of selecting glazing types at Amman. Results (Fig. 8) show that for glazing types, Northern-directed window would not result in any savings compared to the other three orientations. From the payback period graph (Fig. 9), the South window induced the least payback period for all types of glazing. Among the glazing, clear glass, having the shortest payback period (around 2 years for South window). However, it is not recommended, since the glazing types A and B are still reasonable, and more beneficial in terms of energy savings. After the techno-economic evaluation and optimization, the authors concluded that in Amman, the North window should be avoided, and if left with no choice, then glazing type B should only be undertaken as a last resort, due to the fact that if nothing else, it does not induce a loss. For South, East and West,

Table 6
Comparison of total energy savings (%) for the sawtooth toplighting option with different glazing types and orientations and 10% TFR compared with the base case model. A negative value represents an increase in the energy consumed [27].

10% TFR	North				South			
	Sgl (%)	Dbl (%)	DLoE (%)	DRef (%)	Sgl (%)	Dbl (%)	DLoE (%)	DRef (%)
Lighting	58.4	57.4	56.6	47.2	58.4	57.5	56.6	47.9
Cooling	−0.6	1.2	3.4	2.3	−0.2	2.0	4.3	1.3
Total	12.5	13.5	15.0	12.1	12.7	14.2	15.6	11.6
	East				West			
	Sgl (%)	Dbl (%)	LoE (%)	Ref (%)	Sgl (%)	Dbl (%)	LoE (%)	Ref (%)
Lighting	58.1	57.1	56.1	46.3	58.1	56.9	55.8	46.1
Cooling	0.6	1.4	3.2	2.1	−0.8	1.3	3.9	0.7
Total	13.3	13.7	14.7	11.7	12.2	13.5	15.1	10.7

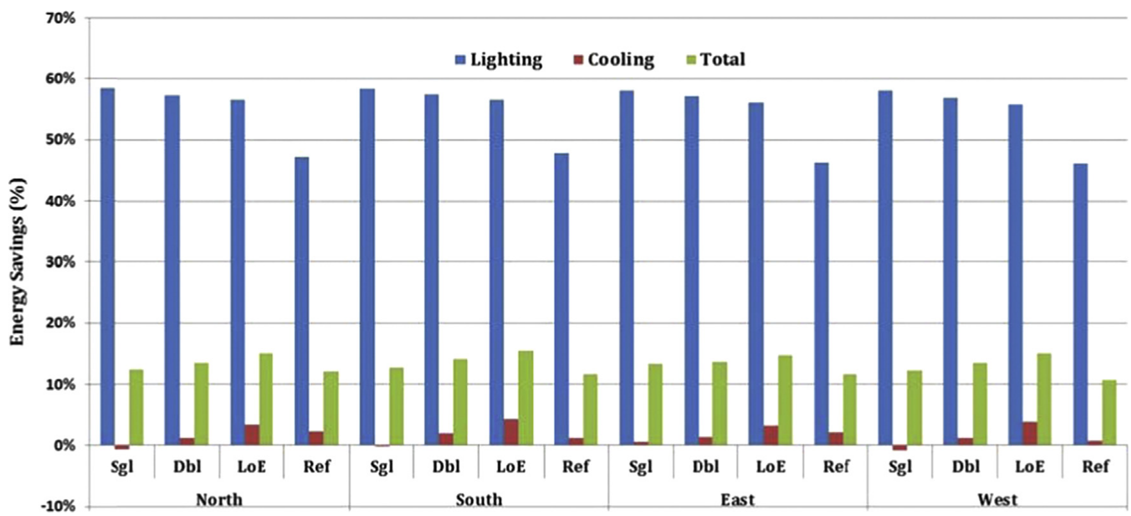

Fig. 7. Lighting, cooling, and total energy savings (%) for the sawtooth toplighting option with different glazing types and orientations compared with the base case model. A negative value represents an increase in the energy consumed [27].

Table 7
Window optimization for fives distinctive climate condition in Asia [5].

Location	Window orientation	WWR	Glazing	*U*-value	SHGC	Tvis
Manila	North	50%	Triple	0.797	0.209	0.433
Taipei	North	50%	Double	1.507	0.249	0.490
Shanghai	South	25%	Double	1.503	0.313	0.600
Seoul	South	25%	Triple	0.796	0.277	0.530
Sapporo	South	25%	Triple	0.796	0.492	0.664

glazing type A is the best choice, followed by type B. The payback period for other glazing is intolerable.

Jaber and Ajib [26] did a sequence thermal optimization of glazing (as in Table 2 and Section 2.1) at Amman, Aqaba and Berlin. Single-glazed window at all sites induced a linear relationship of annual heating/cooling energy and WWR, hence it is unable to undergo optimization, and this also indicated that single-glazed window should be the smallest in size. The same goes to the double-glazed L window in Berlin, due to its relatively low ambient temperatures in winter. Furthermore, Northern windows are also need to be limited to sizes as small as possible, due to its energy losses. The optimization results for glazing are summarized in Table 8.

However, information regarding thermal optimization is inadequate to allow a user to select the glazing type, as this information is bereft of financial considerations. After economic optimization, it is found that windows with double-glazed L are cost viable for Amman and Aqaba. In Amman, double-glazed L window with sizes of 10%, 30%, 20%, 10% for North, South, East and West directions, respectively, recorded the lowest life cycle cost (LCC) and payback periods, while in Aqaba, the lowest LCC and payback period occurred at 10% for all orientations. A minimum LCC and payback period windows for Berlin is double-glazed H, with sizes of 10% for all directions. Technically, a triple-glazed window is more efficient than others, but is financially unfeasible at almost all sites.

3. Dynamic window glazing

Fenestration systems nowadays are more advanced due to the efforts of R&D, especially for window glazing systems, where we passed the era of static glazing, which can only offer single fixed thermal and optical properties. Furthermore, dynamic glazing is one of the active research spot in recent building arenas. More excitingly, some space application materials are now being integrated into energy and building arenas, which include PV cells, aerogel and phase change materials (PCM)…, etc.

There is wide variety of optical switching devices for dynamic glazing in the market nowadays, which includes chromogenic technologies, thermotropics, liquid crystal, and suspended-particles [13,28]. Chromogenic technologies comprises of thermochromic, gasochromic, photochromic and electrochromic (EC) [29]. Among the technologies that we currently have, EC is very popular in the field of glazing technology. Over the past two decades, it is

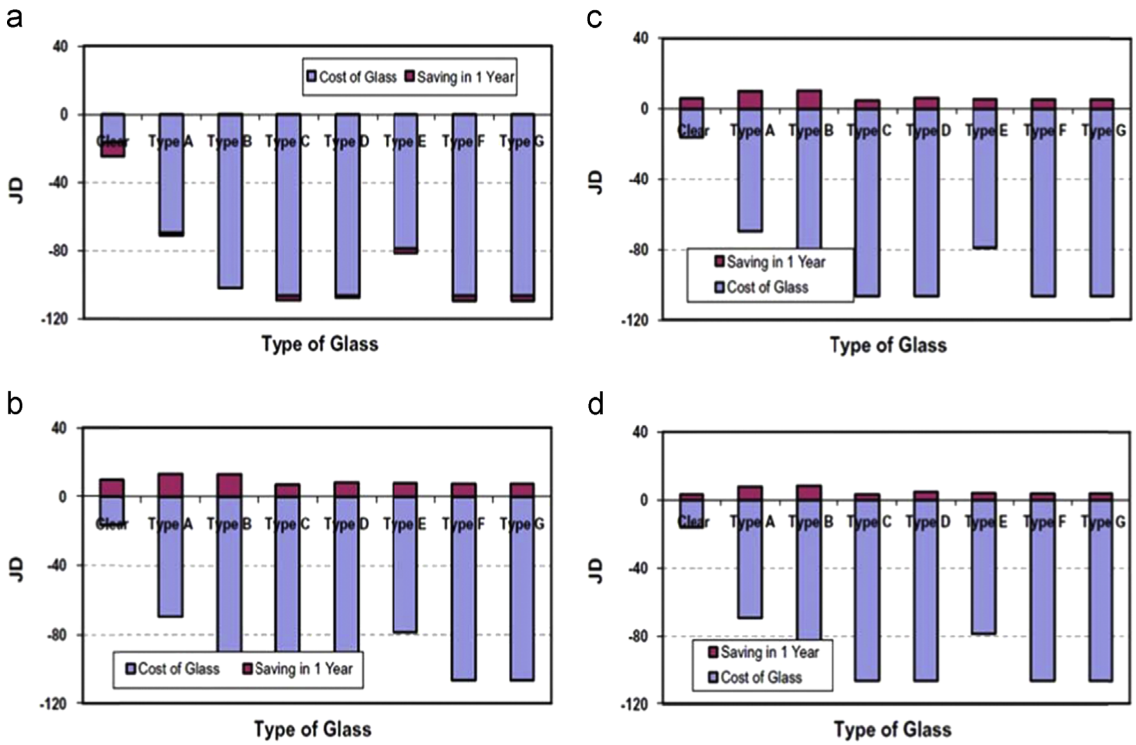

Fig. 8. The glass cost and the saved money (Jordan Dollars) in 1 year for 17% of glazed area in (a) North, (b) South, (c) East and (d) West directions [19].

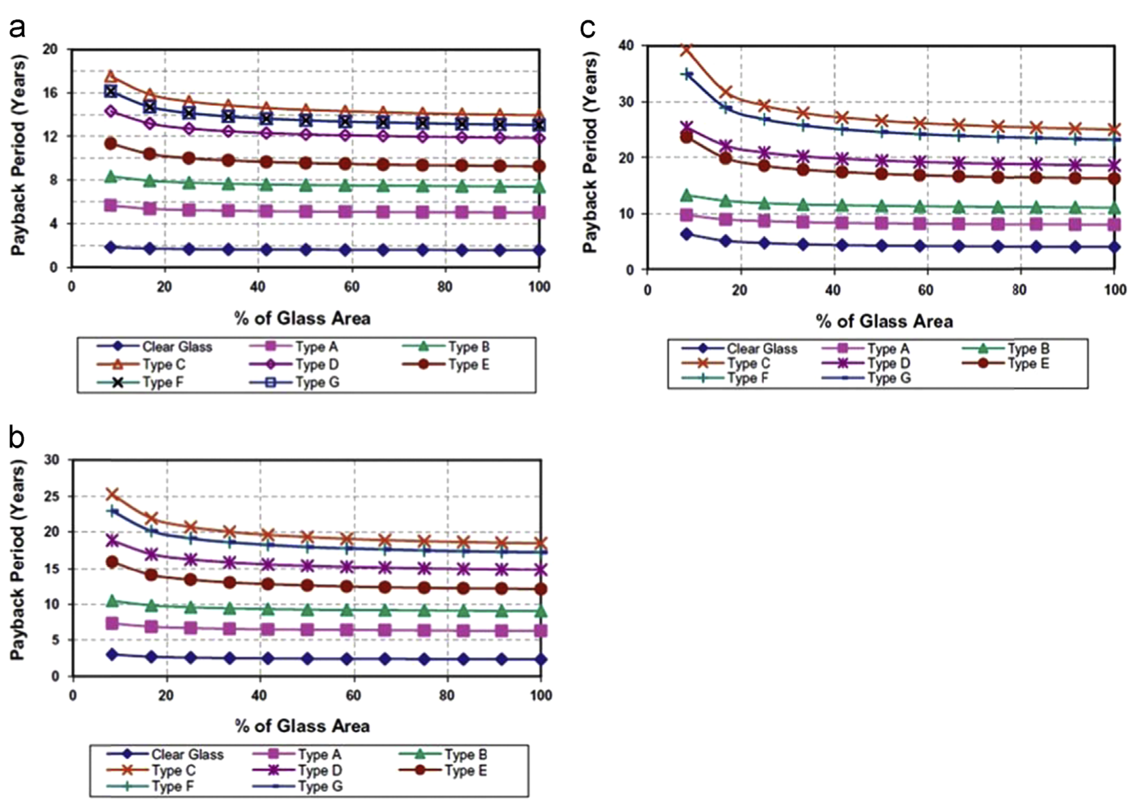

Fig. 9. Payback period of glazing cost in the (a) South, (b) East and (c) West directions as a function of glazing area for different types of glasses [19].

the strongest commercial activity found in Japan, Europe and the USA [13]. Therefore, recent R&Ds are more focused on the verification of the utilisation of EC devices compared to other technologies. According to the state-of-the art review conducted by [12], EC windows seem to be the most promising technology for daylighting and solar energy purposes. The performance of electrochromic windows had been verified in hot climate regions such as California, USA. However, more researches are needed to validate the performance for those windows in a cold climate area. The review, technical information, status of the industry, developments and progress of dynamic glazing had been described by various researchers [11–13,28–30].

Table 8
Thermal optimization of different glazings at all research sites [26].

Sites	Orientation	WWR (%)			
		Single glazed	Double glazed L	Double glazed H	Triple glazed
Amman	N	10	10	10	10
	S	10	40	70	90
	E	10	40	80	90
	W	10	20	70	90
Aqaba	N	10	10	10	10
	S	10	30	80	70
	E	10	20	90	60
	W	10	20	80	70
Berlin	N	10	10	10	10
	S	10	10	40	80
	E	10	10	10	10
	W	10	10	30	70

3.1. *Electrochromic glazing for energy efficient and daylight window*

EC glazings have some advantages over the other dynamic glazings, and are therefore most popular in a particular field. According to Lampert [13], the advantages of EC glazing are listed below:

(i) Power only involved when switching of EC.
(ii) Only small voltage is needed for switching.
(iii) EC have durable memory (12–48 h).
(iv) They are specular in all states.
(v) Large area fabrication is possible for EC.

They also have a wide visible transmittance (Tvis) and solar heat gain coefficient (SHGC): they can be switched from Tvis = 62% and SHGC = 0.47, to a fully tinted state of Tvis $\leq$ 2% and SHGC = 0.09 [31].

Inoue et al. [32] examined the effectiveness of an autonomous responsive dimming (thermotropic) glass panel fabricated with a transparent heating layer and an electrochromic layer to provide additional active dimming control through preliminary experiments and simulations. The proposed window systems with thermotropic glass combine shading direct solar radiation and effective utilisation of daylight, and have energy performances that are as good as or better than those of existing window systems.

Piccolo et al. [33] conducted an experiment on EC small scale test-cell in order to evaluate its daylight performance. The EC small scale test-cell was equipped with a double-glazed EC glazing prototype, and it is tested under real climate conditions of Messina, Italy. Only two main orientations were considered in the experiment: South and West. First of all, the authors characterised the visible transmittance as a function of solar incident angle for both the bleached and coloured state. Results show that the active switching effect of EC glazing, combined with the solar incident angle, resulted in a wide range of selectable illuminance transmittance for local climate conditions. Most importantly, the study revealed that, even though EC glazings are unable to totally avoid direct sunlight glare, it is able to deal effectively with the discomfort glare, due to the diffusion of sunlight. For the South orientation, the EC window is capable of providing adequate daylight for office tasks, while simultaneously reducing the unwanted glare without the assistance of shading. However, the situation was different for the West orientation, due to its high level of direct solar radiation. High illuminance level was recorded in the work place; even the EC glazing was switched to the lowest visible transmittance. Therefore, for the West window, EC glazing was unable to offer comfortable visual level without the aid of additional shading devices.

Piccolo [34] then modified the EC test-cell in order to execute another experiment from the perspective of thermal performance. All of the experimental setups were similar to the visual investigation; the difference is that the measurements were designed to accommodate thermal aspects. The aim of this study is to determine the possible reduction in the cooling load during summer time for climate background of Messina, Italy. The same two orientations were investigated – South (due to its main solar radiation comes from diffuse daylight) and West (due to its interception of direct sunlight). Piccolo et al. [33] used to relate the solar incident angle with visible transmittance, while Piccolo [34] presented the relationship of solar incident angle with solar heat gain:

- Windows with high solar heat transmittances at near-normal incidence directions.
  This occurred during the winter; the solar radiation comes from the low sun height, the sunlight incident angle near to the normal, windows with higher SHGC is a better choice, due to the needs of solar gain in warming up the internal space.
- Windows with low solar heat transmittances at off-normal incidence directions.
  During the summer, the sun radiation comes from the high solar altitude, and the sunlight away from the normal. Hence, windows with lower SHGC are needed to reduce the internal heat gain.

Static glazing is incapable of fulfilling both conditions simultaneously, due to its static transmittance. Nevertheless, the EC window, with its switchable behaviour, is totally different. By the rough estimation computed from the experiment, in the diffuse daylight conditions, the dynamic range for the SHGC obtained was 4.4:1 for fully bleached and fully coloured states. Moreover, the results from this study were similar compared to the results of Piccolo et al. [33]. For a south facing window, EC glazing is able to effectively deal with overheating without compromising the visual aspects, even though there is an absence of additional shading. On the other hand, the EC glazing, in its fully coloured state, is able to reduce overheating and partially control unwanted glares for windows facing west. From a visual perspective, shading may help EC windows to further control glare. However, from a thermal standpoint, especially during the winter, shading might be detrimental to the thermal benefit gained from West windows. Therefore, it is suggested that extra care is needed in order to employ the West facing windows, even if EC glazing is in use.

Maximum daylight and energy efficiency was achieved in a field study that used electrochromic windows. This study was conducted by Lee et al. [35] to measure the lighting energy usage and cooling loads of large, south facing tungsten-oxide absorptive EC windows with the provision of broad switching range in a private office setting. A two zone EC window configuration was provided to attain the objective of visual comfort through EC control and Venetian blinds. An average daily lighting energy savings of 10 $\pm$ 15% over reference case with fully lowered Venetian blinds was obtained through this configuration. In addition, it also provided a cooling reduction of 0 $\pm$ 3%. Lighting savings of 44 $\pm$ 11% was obtained, provided that the study was based on an assumption of no daylight controls. In the presence of a critical demand response mode that was the maximum at 19–26% on clear sunny days, window cooling loads led to reduction in peak demand. In terms of the reference cases with and without day lighting controls, the peak reduction in lighting energy varied from 0% or 72% to 100%.

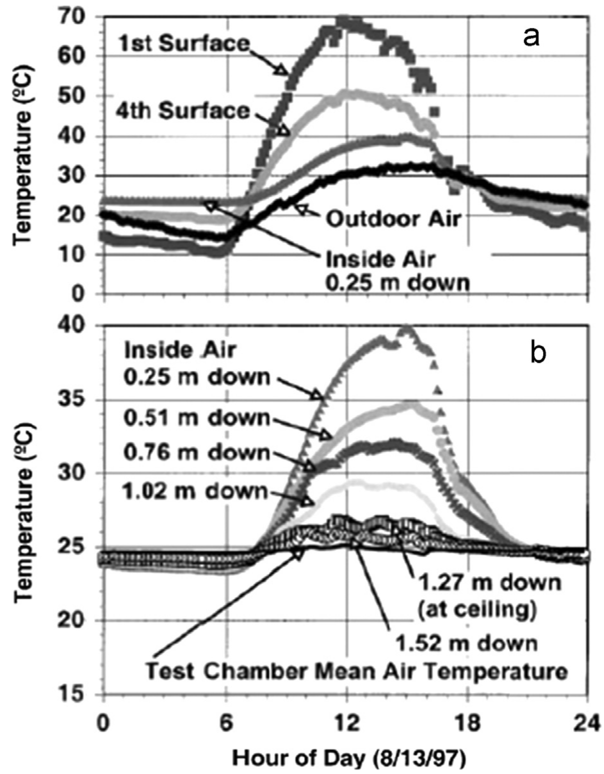

Fig. 10. Measured temperatures for sample EC-1 in its fully coloured state on a clear day. (a) Skylight surface temperatures and nearby air temperatures. (b) Air temperatures in the light well profile compared with the mean calorimeter air temperature [37].

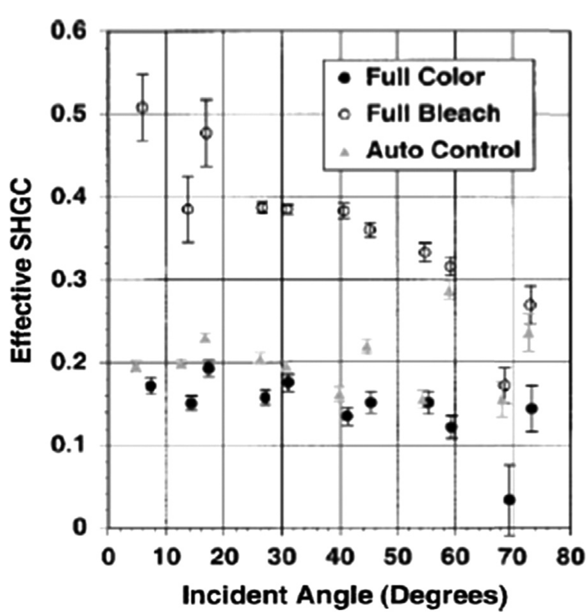

Fig. 11. Measured beam solar heat gain coefficients (SHGC) for sample EC-1.The results from two static tests are shown, one with the sample in its fully bleached state (open circles) and one in its fully coloured state (solid circles). Also shown is a test in which the coloration was dynamically controlled to maintain a constant illuminance in the test chamber [37].

The electrochromic glazing, with its switchable optical effect, enable the thermal energy savings by varying properties such as SHGC. However, visual tasks are always contradicted by thermal tasks. Darkening the electrochromic glazing reduces the solar heat gain, due to the reflection of solar radiation to external environment, but at the same time, the darken electrochromic window is detrimental vis-à-vis daylighting the space. Therefore, other types of electrochromic material had been developed to overcome this adverse effect, namely near-infrared switching electrochromic (NEC). It has the same dynamic optical properties compared to the conventional electrochromic glazing, with the exception of the fact that it remains transparent to visible light, creating more daylit opportunities [36]. Performance of the NEC had been investigated by DeForest et al. [36], based on different climate zones throughout United States (US). The comparison of NEC with static glazing will be presented in the next section.

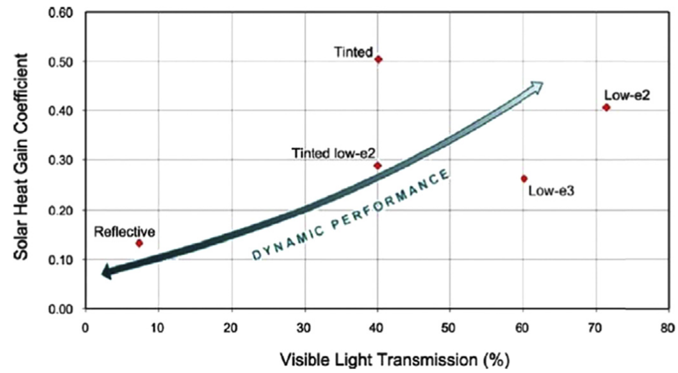

Fig. 12. Glazing properties comparison between EC glazing and some static glazings [27].

Table 9
Daily lighting energy saving comparison for static glazing and electrochromi glazing [39].

Comparison of	Percentage of daily lighting energy saving (between 6.00 am and 6.00 pm) (%)
EC window/unshaded window, Tvis = 0.15	44–59
EC window/unshaded window, Tvis = 0.50	8–23

Prototype EC glazings skylights used in a room-sized calorimetric test facility in Reno, Nevada, USA were observed by Klems to evaluate their thermal performance [37] and also highlighted the issues in testing primarily associated to the dynamic switching nature of the glazings. The facility was tested under ambient outdoor summer conditions. In the light well, significant air temperature stratifications were seen, specifically when the EC sample was in its "fully coloured" state, as shown by the plots for a single reasonably clear day in Fig. 10.

A low solar heat gain coefficient SHGC is obtained by changing the EC transmittance in the visible range from high wavelength to low wavelength, as shown in Fig. 11. The incidence angle will determine the SHGC in a clear state. Same is the case with the sample for comparison, of which a data is shown. The SHGC was however determined by the incident angle in the maximally coloured state, which would have been expected for highly absorbent glazings.

Performance of the glazings was only studied for summer settings and it only observed the static properties. Significant reductions in the SHGC are also implied by the electrically controlled reductions in visible transmittance, as depicted by the results. In the peak summer conditions, EC glazings perform similarly, as it allows solar light and heat in other cases due to the highly absorbent low SHGC conventional skylights.

Gugliermetti and Bisegna [38] analysed the optimum operation for EC windows based on two modes: (1) on/off control strategy (OCS – immediately switching of state), and (2) linear control

Table 10
Annual lighting usage that maintains 600 lux at the workplane [41].

	Electrochromic window		Reference window
	Lighting energy (kWh/a)	Saving vs. reference window (%)	Lighting energy (kWh/a)
Without overhang			
Hourly blind control	240	−62	148
Daily blind control	277	48	536
With overhang			
Hourly blind control	255	−54	166
Daily blind control	287	37	457

Table 11
Energy saving comparison [31].

	% Annual energy savings		
	Minneapolis	Washington	Arizona
EC double pane compared to			
Single-pane clear	45	45	46
ASHRAE 2007 Double pane	21	22	22
Commercial double pane	4	10	20
EC triple pane compared to			
Single-pane clear	57	53	NA
ASHRAE 2007 triple pane	37	34	NA
Commercial triple pane	14	16	NA

strategy (LCS – gradually collar switching). The EC windows are integrated with artificial light dimming control in order to maximise the energy savings and visual comfort. This study revealed that the total energy to operate OCS and LCS is similar. However, LCS is more favourable, due to its provision of visual comfort and the increasing number of dimming zones (least utilisation of electrical light).

3.2. Comparison of electrochromic glazing with static glazing

Sbar et al. [31] stated that the current static glazing technologies are unable to supersede the energy savings achieved by dynamic glazing, due to fact that static glazing offers only a single fixed optical transmission. Fig. 12 compares the glazing properties of EC glazing and static glazing. In order to prove that dynamic glazing is more advanced than static glazing, plenty of researchers used to compare the performance of electrochromic glazing with static glazing. This section presented the results of the comparison made by some researchers.

Lee et al. [40] conducted a field study at Berkeley, California in order to define the daylight performance of electrochromic windows that are integrated with lighting control system in a full-scale office test bed. Three identical large-area windows were installed side-by-side on the test beds. The windows were installed with different glazing: (1) unshaded window with Tvis=0.50, (2) unshaded window with Tvis=0.15 and (3) electrochromic window with Tvis=0.05–0.60. The lighting of those three rooms was modulated so that the rooms are filled with sufficient illuminance level for office tasks. Table 9 shows the results of comparison for those glazing.

As compared to the conventional double glazed windows, the EC windows can give higher energy performance. This was concluded from the computer modelling of the energy efficiency of EC windows in buildings done by Lampert [41] about 30% better energy savings are obtained as compared to conventional glazings.

Fernandes et al. [42] conducted a simulation study in Berkeley, California in order to determine the potential lighting energy saving by using EC windows. A reference window, with clear glazing of Tvis=0.60 is used for comparison purposes with the EC window in the Southern orientation. On top of that, blinds were integrated for both windows with two adjusting modes: hourly blind control and daily blind control. Hourly blind control means the height and slat angle of the blinds were adjusted hourly, while the daily mode involves only one-time adjustment on a designated day. Table 10 shows the results of annual lighting energy consumption with an illuminance setpoint=600 lux.

Surprisingly, the annual lighting energy usages for EC window were higher than that in the reference window regardless of whether the windows were integrated with an overhang or not. If the blinds were adjusted hourly, the yearly lighting energy of electrochromic window were 62% and 54% higher than the reference window for the case of without and with overhangs, respectively. Results indicated that hourly control blinds were more suitable to be combined with ordinary clear glass instead of EC glazing. However, in reality, the adjustment of blinds was not that frequent, and thus the daily control mode was simulated by the researchers. With this mode, the EC window was able to achieve savings of up to 48% (without overhang) and 37% (with overhang) in annual lighting electricity. This study revealed a very important point: the energy performance of the EC window is heavily dependent on how the blinds are being controlled.

Sbar et al. [31] compared EC window and some static glazings in three climates in the US. Table 11 shows the results of the energy performance comparison.

Note that the EC glazings were also compared with the ASHRAE 2007 standard code of window properties for sites in Arizona (hot and dry climate), Minneapolis (cold climate) and Washington (mixed hot and cold climate). Also, commercial glazing means glazings that are commercially available. When EC glazing is compared to single pane clear glass glazing, there was a significant amount of energy being saved, ≥45%, at the three locations. This is a huge encouragement for designers or building owners, due to the fact that there were still many buildings at those sites utilising single pane windows.

A simulation study was done by Lee and Tavil [43] that showed that EC windows considerably enhance visual ease without taking away the advantages offered in terms of energy efficiency. The experiment was repeated with the same size of the window, divided window wall and overhang for the EC configuration. This was used to compare the performance of the EC window in the presence of the spectrally selective low-E window. The average annual daylight glare index (DGI) was reduced to a greater extent by the EC windows with overhangs. Annual savings were also obtained when the window area was increased. Hot and cold climates were both considered in the study for Houston and Chicago. The total primary annual energy usage increased by 20–5% for moderate sized windows in both climates, when the simulation study was done. But in case of large sized windows in Houston and Chicago, the total primary energy usage was reduced by 5%. The highest electric demand was reduced by 7–8% for moderate sized windows and for large sized windows in both the climates, the electricity demand was reduced by 14–16%. If the cases referred in this study did not have exterior shading and technologically advanced static glass, then major energy and peak demand reductions could be achieved.

Finally, DeForest et al. [36] compared the NEC with static glazing for commercial and residential buildings in a 16 climate-representative reference cities from the US. NEC glazings are

Table 12
Comparison of reduction in cooling (C), heating (H) and total energy (T) in three different orientations [43].

Glazings	East Reductions of annual energy demand (%)			West			South		
Thermotropic compared to	*C*	*H*	*T*	*C*	*H*	*T*	*C*	*H*	*T*
Double glazed	6.3	−5.5	1.0	19.0	−7.3	8.5	10.2	−8.7	2.5
Double glazed tinted	−9.8	8.5	−0.2	3.3	6.0	4.6	−6.6	8.9	1.0

capable of limiting the solar heat gain, and simultaneously allow the passage of visible light so that it would not compromise the daylight transmission. The blocking state of NEC blocks only solar gain, and the transmitting state means the solar heat is allowed to enter into space. Since the NEC only blocks solar heat, visual aspects such as daylight level and glare are not discussed in this work. In hotter regions, NEC shows better performance than the static glazing on a heating and cooling energy viewpoint. Both commercial and residential buildings in the hot region prefer blocking state. However, even NEC, in its highest blocking state, is still transmitting 30% of the solar energy (visible light) into space, due to its nature of high transparency for daylight. Further increase of the NEC solar heat blocking state would certainly weaken the visible transmittance. In a residential building, where visual aspects were less intense, the solar heat blocking state will not be very restricted. On the other hand, in some hot area's commercial building, the optimization of SHGC and visual elements are needed, and this will involve the minimum sacrifice of one of those aspects. Hence, the authors concluded that NEC may be more suitable for applications in residential areas and cold climate regions. Furthermore, the researchers also suggested that future works in this task may involve financial aspects in order to further verify the performances of NEC as a whole.

4. Thermotropic windows

Thermotropic glazing is one of the smart and non-electrically activated glazings. It is activated by heat instead of electricity. When it's critical temperature is exceeded, it goes through a physical phase transformation, altering the radical property, thus triggering the scattering or absorption of light [28]. Changing physical phases may cause the loss of certain visual parts of the spectrum, diminishing the window's view in the process. However, it performed better in the near infrared region, and is capable of providing diffuse daylight [30].

Yao and Zhu [44] investigated the indoor thermal environmental, energy and daylighting performance for thermotropic windows, based on the typical hot summer and cold winter city – Hangzhou, China. The thermotropic window was applied to the highly uncomfortable environment and compared with the double-glazed and tinted double-glazed windows in the direction to the west. Results show that thermotropic double-glazed window was able to greatly mitigate the uncomfortable conditions, and the comfortable levels can be increased by 14.5% and 2.4% compared to double-glazed and tinted double-glazed windows, respectively. Table 12 shows the comparison of energy reduction for three types of glazing in the East, West and South orientations.

From Table 12, thermotropic window performed better in the West orientation compared to others. This is due to the West window receiving the most solar heat, and this triggered the properties of thermotropic window, providing thermal comfort in the space. The performance of thermotropic window in the South orientation is quite acceptable, but not in the East orientation.

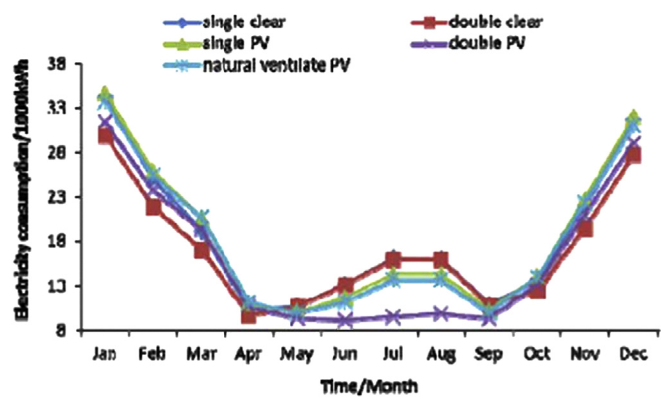

Fig. 13. Monthly electricity consumption for the five glazing systems used in office building of Harbin [47].

In term of daylighting, thermotropic performed better than the other two glazing in terms of illumination uniformity on East and South direction. Again, in the West direction, thermotropic window was better than double-glazed and double-glazed tinted glazing windows. It provided a proper indoor illuminance, sans distributing glare to the occupants. From the above study, thermotropic window seems to work effectively in the West direction compared to others, which is in line with the opinion posited by Mahdavinejad et al. [30].

Similar with the other dynamic glazing (except electrochromic window), the performance of the thermotropic window required further verification via researches and development. Besides, R&D is expected to address certain issues regarding thermotropics, such as low visibilities.

5. PV windows

Owing to the current R&D environment, windows are able to fulfil other needs; electricity generation while maintaining its normal function. The solar cells were fabricated on the transparent glass, and are made into solar cells via glazing. The potential of this alternative uses of window seems expansive and promising to the building industry [14]. However, the available Tvis for PV glazing may be lower compared to other glazings, since higher Tvis will reduce the sun radiation for solar cells to produce electricity. Therefore, one of the challenges for solar cells window is the optimization of two features: daylighting and electricity generation [14,45].

The capability of photovoltaic ventilated glazing technology was studied by Chow et al. [46] to minimise the energy daylight usage, green electric power generation in warm climates and air conditioning loads. In comparison to the non-transparent c-Si solar cells a-semi-transparent Si glazing performs better in a working environment. A small office room in Hong Kong with various window orientations was used in the study to analyse the integrated performance. A high electricity saving was obtained by the transmittance of the solar cells in the range of 0.45–0.55.

The three types of PV glazing systems were compared by Guo et al. [47] in a simulation study used an office building in Shanghai located in hot summer conditions and cold winter conditions of China for the conservation of energy. A single clean SC was used as the basis for comparing the simulation of the annual electricity consumption and it showed savings rate of a single PV glazing system (SPV) to be about 3.6%. In the case of a double PV glazing system the saving rate was about 4.8%, while 6.7% saving was obtained for natural ventilated PV glazing system.

The thermal performance and energy savings of five types of glazing systems for office buildings in various zones of China were studied by Li et al. [48]. The DPV performance was the best in the extreme cold conditions of Harbin with an energy saving rate of 12.3% when compared with SC (Fig. 13). The double clear was next in performance with an energy saving rate of 8.1%, while NVPV was the last in performance with an energy saving rate of 2.7%. The DPV's energy saving rate was 0.67%. The DPV's performed the best in the cold regions of Beijing with an energy savings of 4.9% when compared with SC. The DC with 4.5% saving rate was in second place, while NVPV with energy saving rate of 3.3% was third in place, while SPV gave a 1.2% of energy saving rate.

NVPV glazing system was the best one in the hot summer/cold winter zone of Shanghai, while with energy saving rate of 4.3% DPV came in second and DC with an energy saving rate of 2.4% was third in place. The SPV had an energy saving rate of 1.8%. NVPV was the best glazing system to be used in the hot summer/warm winter zones of Shenzhen as it gave an energy saving rate of 10% as compared to SC. The DPV gave an energy saving rate of 8.3% and SPV gave an energy saving rate of 6.6% to be the least performing glazing. The DC consumed 0.3% annual total electricity more than SC.

Miyazaki et al. [49] run a simulation investigation on the solar cells glazing in an office building in Tokyo, Japan, for the optimum solar cell transmittance and window size, and evaluate the energy performance of the building. The PV cells used in this study were transparent amorphous silicon solar cell developed by Sanyo Electric Co., Ltd. The performance of the solar cell glazing was compared with the standard mode (original thermal properties of that building). Fig. 14 demonstrates the contradiction of lighting energy consumption of PV glazing.

Due to the contradictions above, we need to look at the total energy consumption for the building in order to optimize the window size and solar cell transmittance. Fig. 15 shows the total energy usage with respect to solar cell transmittances.

From the results above, the optimum WWR and solar transmittances for WWR of 30%, 40% and 50% were 0.8, 0.6 and 0.4, respectively. Also, the combination of 50% WWR and 40% solar cell transmittance achieved the lowest energy usage compared to the others. This combination also enhances the energy performance of the building by 54% compared to the standard mode.

Lu and Law [50] simulated a case study in Hong Kong to determine the thermal and visual properties of semi-transparent single-glazed photovoltaic window. They revealed that with a solar cell area ratio of 80%, a reduction of around 65% of solar heat gain can be achieved. This reduction in turn causes the cooling load demand to decrease in the tropical region, such as Hong Kong. Typical Hong Kong air-conditioning includes two types: water-cooled and air-cooled air-conditioning. The annual cooling electricity benefits were 900 kWh and 1300 kWh for water-cooled and air-cooled air-conditioning systems, correspondingly. The authors also found that, in Hong Kong, the South–East orientation received the highest daylight illuminance level, and it precipitated the highest energy production. Thus, the South–East direction turned out to be the optimal orientation for total energy performance.

Literature study shows that PV glazing with high Tvis is good choice for daylighting, but it is adverse towards electricity generation. Hence, designer or builders should take precedence over daylighting and electricity generation in order to achieve expected outcomes. However, due to imperfections, optimization can be considered as the best solution for a balanced outcome.

The potential energy savings and energy generation of semi-transparent PV windows in the office buildings of Brazil was

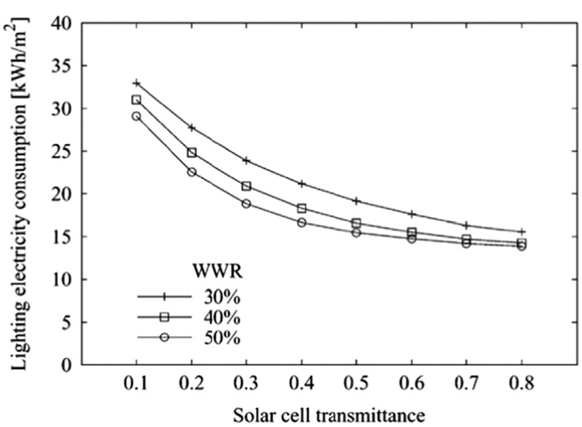

Fig. 14. Annual lighting energy consumption of the building as a function of solar cell transmittance for different window size [48].

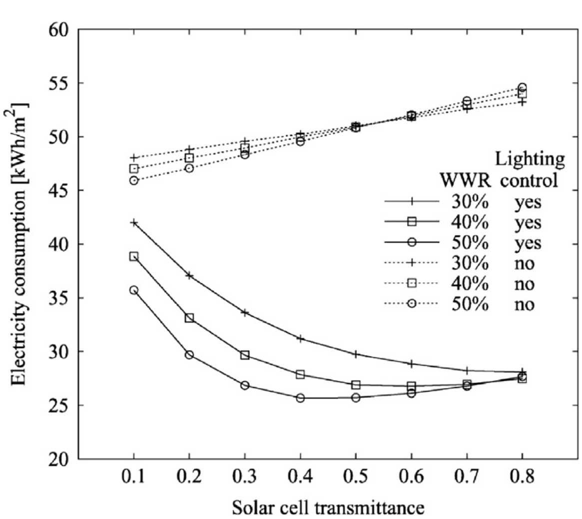

Fig. 15. Annual electricity consumption (cooling+heating+lighting) of the building with respect to solar cell transmittance [48].

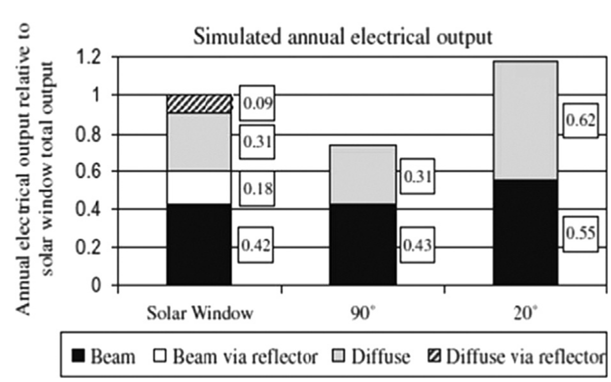

Fig. 16. The annual electrical output from the prototype solar window and from two flat PV-modules on a wall at 90° tilt and on a roof at 20° tilt [52].

studied by Didoné and Wagner [51] through a method developed by them. The possibility of decreasing the energy consumption of artificial lighting and air-conditioning through adequate control systems and energy generation through semi-transparent PV panels in windows was depicted by the results of the study. The high potential of this technology with respect to Brazil was indicated, although the study only considered only one type of building geometry.

The performance of a new type of the PV slat window was studied by Khedari et al. [52] with respect to the allowing daylight and its ability to minimise direct heat gains and allow indoor air movement, thus leading to thermal comfort of residents. According to the results, about 15 W of power can be produced by the multi-purpose PV-SW. this will in addition also reduce the indoor temperature and provide sufficient illumination for residential projects. About 750 lux with slats angle of 68° was the maximum measurement obtained for illumination. In comparison to the room equipped with transparent slats, the room temperature in this case was about 2–3° centigrade lower.

An absorber with solar cells lamination is termed as the PV/T hybrid. A solar window can be manufactured with a PV/T hybrid collector with tiltable insulated reflectors which will cut down the solar electricity costs. A multifunctional PV/T hybrid integrated window is used instead of PV modules, solar thermal collectors and sun shades. Reflectors can only reflect a controlled amount of radiation into the building. Thermal losses occurring through the window are also reduced by the reflectors. The insulated reflector will also do the same and reduce thermal losses through the window. The performance of this solar window was studied by Davidsson et al. [53] as an effective way to save energy for heating and minimising the total costs of PV and reducing dependency of a building on the solar thermal systems. The significance of using diffuse radiation was evident from the results of the simulated annual electrical production. Diffuse radiation led to a reduction in the electrical energy by 40%. About 35% additional electrical energy per unit is produced by the solar windows as compared to the flat PV module positioned on a wall at a 90° tilt (Fig. 16).

More thermal energy per unit of absorber area was produced by the solar windows in comparison to the flat plate solar collector. Provided that the roof of Solgården at a 20° tilt, as indicated by the simulated results of Fig. 17.

The annual output increased by around 5% at an optimum tilt of 45°. Same amount of electrical energy was produced by the solar window placed vertically on the wall as a roof integrated PV module per unit cell area. The same amount of thermal energy per unit of an absorber area is produced by the solar window which has a solar collector tilted at 20°.

The HCRI-BIPV smart window was developed by Chen et al. [54] to enhance the indoor thermal performance. The office was studied between 8 am and 5 pm conforming to the office research scale. The base line of the temperature sensor to drive the window system was maintained at the key level temperature of 26°. The temperature varied by 16.5 ° C, when the windows were opened or closed. Passive energy was offered by the HCRI-BIPV smart windows to load power and enhance the thermal environment if the interior through natural ventilation (Fig. 18).

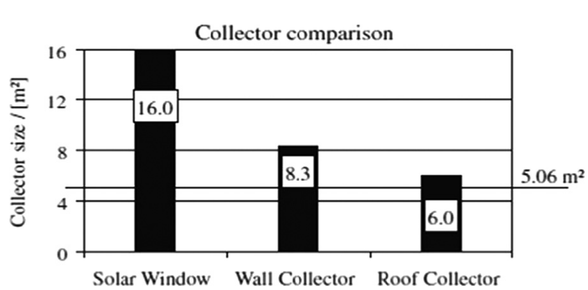

Fig. 17. The required areas of the wall collector and the roof collector to produce an equal annual amount of thermal energy compared to the Solgården solar window. The wall collector is placed vertically and the roof collector is installed at 20° tilt [52].

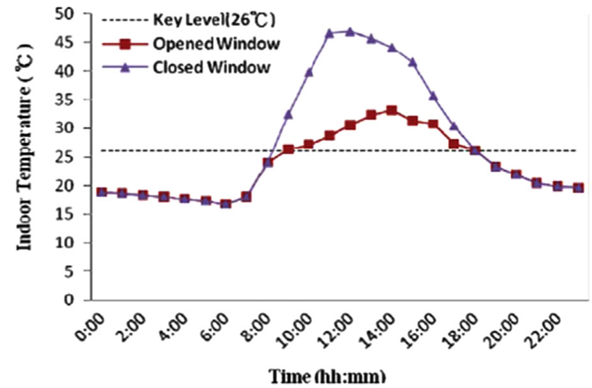

Fig. 18. The indoor thermal analysis between the window opened and closed [53].

6. Innovative glazing

This section reviewed four relatively new technologies in the fenestration – aerogel and phase change material (PCM), prismatic and vacuum glazing.

6.1. Aerogel glazing

Aerogel, better known as solid air, is an insulator initially developed by NASA (NASA 2005 in [55]). Aerogels can be made from various materials such as silica, alumina, transition and lanthanide metal oxides, metal chalcogenides, organic and inorganic polymers, and carbon [55]. They are solid materials having the lowest solid density, ranging from 1 to 150 kg/m^3 [14,55], and typically 90–99.8% air [55]. Aerogels are well known for its weight, for instance, Bahaj et al. [55] reported that aerogel enclosed with polycarbonate weigh 20% less than an equivalent glass unit, but has 200 times the impact strength. Also, it is famous for its *U*-value; a 25 mm thick aerogel panel would have an approximate *U*-value of 0.57 W/m^2 K. This is compared to an equivalent standard double-glazed unit with the same thickness (*U*-value = 1.4 W/m^2 K), the *U*-value of aerogel is almost 2.5 times lower than the double-glazed unit. However, aerogel is not without its imperfections. The low Tvis, together with its high cost, are some of its main drawbacks [14]. However, recent advances in R&D in this field have begun to directly address and mitigate these concerns.

Buratti and Moretti [56] investigated the performances two types of aerogel glazing – monolithic (Tvis = 0.60) and granular (Tvis = 0.27). Compared to a low-e double glazed window, monolithic aerogel enable a reduction of 55% heat losses, with only a 25% loss in light transmittance, while the granular aerogel introduced a 25% drop in heat losses, but a 66% decrease in transmission of light. Buratti and Moretti [56] fabricated a window prototype with the granular aerogel in the interspace of the window. The aluminium frame aerogel window prototype performed better compared to the same air interspace aluminium low-e window by decreasing thermal transmittance to 23%. Moreover, it also improved the sound insulation of the window.

In the same year, Buratti and Moretti [57] published another paper that compared various high performances glazings, including monolithic and granular aerogel, and compared them with the Italian *U*-value limit. Fig. 19 shows the results of the study. From

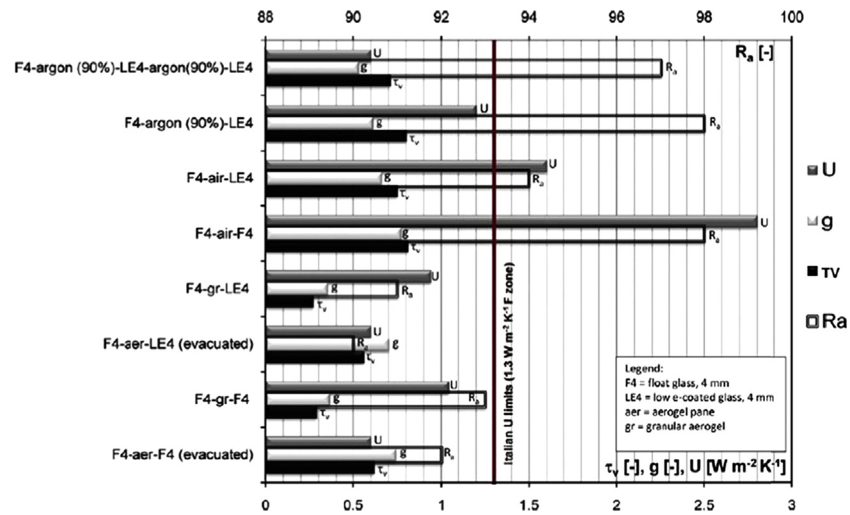

Fig. 19. Performance comparison of aerogel and conventional glazing [56].

the results, monolithic aerogel is the most promising glazing, compared to the others.

Bahaj et al. [55] reviewed a finding of Schultz et al. [58], where it is stated that largest aerogel windows to date (until 2005) are nearly 1 m^2 in size. However, Bahaj et al. [55] also reported that there was significant capacity of translucent aerogel curtain walling beginning to appear in the market in 2006. In the state-of-the-art review (2011) of aerogel in building applications conducted by Baetens et al. [59]; it is reported that buildings had already employed aerogel in its curtain walls and skyroofs. This is indicative of a rapid pace of R&D in aerogel, and its market is expected to expand in the year 2013 onwards.

Indeed, Baetens et al. [59] proved the rapid spread of aerogel in the market by quoting a report written by Cagliardi [60]: the global insulation market is about 29M$. Starting from year 2003 to 2008, the global demand for aerogel tripled to 83M$, and it is expected to reach 646M$ by 2013. Aerogel is capable of providing large energy saving in future windows and skylights, and it is targeting large profitable markets across many sectors, such as building insulation, space vehicles, airplane, automobiles, and appliances insulation [56,59].

6.2. Phase change material glazing

Simple glass windows are vonerable to incident solar radiation penetrating easily through a simple clear glass sheet whose transmittance is of the order of 90%. The development of new materials, new technologies and new strategies for reducing energy consumption led to enhance research and development of more efficient windows. The selective properties due to deposited films on the glass sheets allow changing the transmittance, reflectance and absorptance of the window. These films can be designed to absorb or reflect according to the wavelength of the incident radiation. A vast review of technologies of selective films is reported by Lampert [13]. The use of absorbing gases filling the gap between glass sheets appears to be an alternative solution for thermally insulated glass windows. The other options one may incorporate filling materials such as silica aerogel or a phase change material (PCM) [61]. PV cells, aerogel and PCM, are undergoing a similar renaissance; they are firstly developed for space applications, and then employed by other sectors for their valuable benefits. PCM is able to store or release significant amount of energy via the mechanism of melting and solidification [62].

Various studies have created simple models for spectral radiations to study the use of gas having properties of infrared radiation. Ismail et al. reported that the thermal efficiency of an absorbing gas filled glass window can be compared with one with phase change material filled instead of gas [61]. The windows were subjected to solar radiations in hot climatic conditions. According to the results, more efficiency was indicated by the gas mixture filled double panel glass window and constructed with reflective type of glass. It also had factor '*F*' ranging from 0.55 to 0.65. A factor '*F*' ranging from 0.65 to 0.80 was indicated by the PCM filled in double glass window.

The thermal and optical characteristics of the PCM RT27 were explained by Gowreesunker et al. [63] reported on the thermal and optical characterization of PCM RT27 using the T-history method and principles of spectrophotometry, respectively, and on the experimental and numerical performance evaluation of a PCM-glazed unit. The results are as follows. (i) During rapid phase changes, the transmittance spectra from the PCM are unstable, whereas under stable conditions, visible transmittance values of 90% and 40% are obtained for the liquid and solid phases, respectively. (ii) The radiation scattering effects are dominant in the solid phase of the PCM, whereas radiation absorption dominates in the liquid phase. (iii) The optical/radiation performance of PCM can be successfully modelled using the liquid fraction term as the main variable. (iv) The addition of PCM improves the thermal mass of the unit during phase change, but risks of overheating may be a significant factor after the PCM has melted. (v) Although the daylighting aspects of PCM-glazed units are favourable, the change in appearance as the PCM changes phase may be a limiting factor in PCM-glazed units.

The melting and solidification process requires a few hours. During these processes, the temperature of PCM is maintained at a constant level. The PCM in a total liquid state will behave similar to other sensible heat storage material [62]. Also, the liquid state PCM is non-scattering, clear and transparent homogeneous fluids, while solid PCM possess an appearance that is non-transparent [62]. PCM is well-known for its ability to absorb and store most of the part of solar infrared (IR) radiation, but allows solar visible radiation into its internal space [64]. Hence, it is predicted that PCM is likely to be used in a building's envelop and fenestration applications in the coming years [14].

A numerical model was developed by Goia et al. [65] that describe the thermo-physical characteristics of a phase change material layer combined with various other transparent materials for the numerical analysis of various PCM glazing system configurations. The prospects and shortcomings of the mathematical model were shown through the comparison between the simulations and the experimental data of a simple phase change material glazing configuration. There is a lack of accuracy in the results of the comparative analysis between the simulated and transmitted radiations and heat fluxes, although the simulated data and the experimental data on the surface glazings are in close proximity to each other. The thermo-physical behaviour of the system is well predicted by the numerical tools. Simulations on various other configurations of PCM glazing systems can be achieved by initiating from these numerical results.

Ismail and Henriquez [66] used a double sealed glass filled with a phase change medium (PCM) whose fusion temperature is determined by solar–thermal calculations as a different approach for thermal effective windows. The investigation includes modelling of the heat and radiation transfer through a composite window and optical investigation of conventional and PCM filled windows, testing of the window and comparison with numerical simulations. The results indicated big reductions in the energy transmitted, especially in the infra-red and ultraviolet regions, while maintaining a good visibility.

Weinläder et al. [62] tested the performance of three types of South PCM window with different melting points in Würzburg, Germany. The performances were then compared with a double-glazed window lacking protection from the sun. All PCM outperformed the double-glazed unit, especially during winter. All PCMs were able to reduce 30% heat losses relative to the reference window. Moreover, all PCMs possess solar gains below 0.50, although during the winter daytime, double-glazing shows higher solar heat gain, but this also induced great heat losses during the night. PCM achieve moderate and slow heat gains during daytime and very low heat losses during night time. However, this might be beneficial to winter evenings, due to PCM releasing its energy to the surroundings during the night; the thermal energy gains from PCM phase transition maintain the thermal comfort of the space. Overall, the PCM glazing imposed a more equalised energy balance to the space.

During summer, in daytime, PCM showed a 25% reduction in energy gains compared to the double-glazed unit, thus reducing the peak cooling loads. Nevertheless, during the evening and night, PCM solidification causes the temperature of the space to increase, which is highly undesirable during the summer. If PCM is used in an office building, then this should not be a problem, due to the night time thermal comfort of the office not being a critical issue. Moreover, the heat gains can be drawn off by night-time ventilation.

Goia [64] discovered a vital fact during his research; out of all the configurations being tested, he found that the configuration with the PCM facing the outdoors is superior in terms of thermal comfort. Besides, Goia [64] agrees with the findings of Weinläder et al. [62] that PCM helps reduce the solar heat gain of the building during daytime, and precipitates a more stable indoor thermal environment in the summer. However, the reduction in solar heat gain in winter is unfavourable.

Goia et al. [67] compared clear glass double-glazed unit and PCM double-glazed unit. Overall, PCM's performance is superior to clear glass most of the time. It is found that PCM offered greater benefits if the outdoor solar irradiance is higher. Conversely, the thermal performances of PCM resemble the clear glass. On top of that, extra attention must be paid during selecting the melting point of the PCM. If the PCM's melting is too low for the summer, then the interior pane will reach quite high temperatures, and leave a negative impact to thermal comfort in space. However, contradictorily, PCM with lower melting points are favoured during winter.

The PCM's phase change cycle seems capable of stabilising the internal environment in thermal balance, thus easing the heating and cooling tension of the building. Above all, for building applications, careful attention must be paid in choosing the PCM's melting point, climates conditions, desired indoor temperature, and its properties [14]. Also, most current researches focus upon the thermal element, and future R&D attempt to verify optical properties. In fact, Weinläder et al. [62] mentioned that not all architects or planner can accept the PCM's visual properties and its accompanying effect. He suggested that the PCM window is best for a space that does not rely on visual aspects for any of its intended functions.

6.3. *Prismatic glazing*

A glazing unit with two prismatic planes was used by Lorenz [68] to study solar control, day lighting and energy conservations. The ribs of lights arranged in a prismatic fashion at the plane are basically inclines from a certain angle to the horizontal plane within the window, which shows the same cross-sections in the shape of a right-angled triangle with a certain normal prism angle. These planes are positioned face to face with a small gap in between them. Windows with regular tilt angles and windows having directions with considerable solar radiations at locations

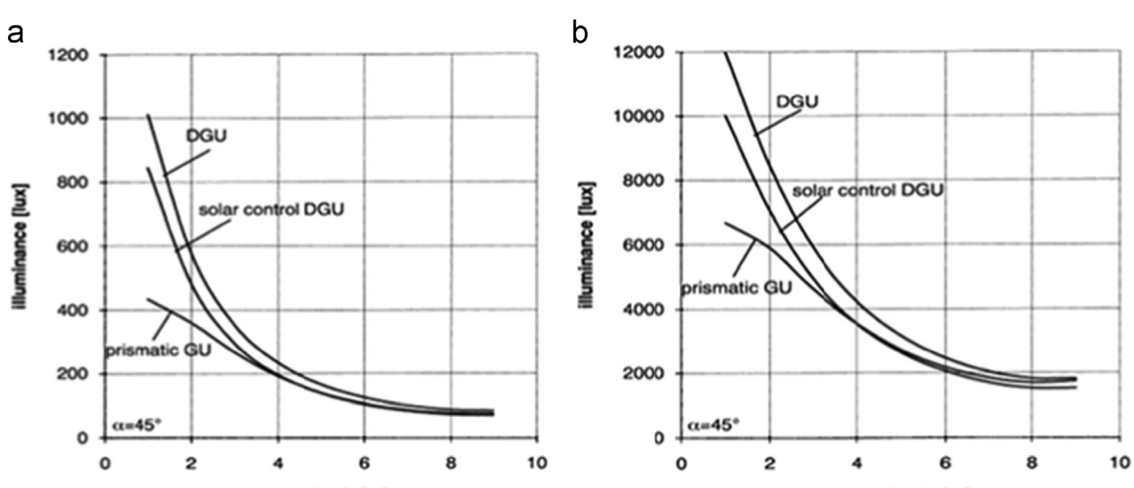

Fig. 20. The illuminance within the symmetry plane of the test room at a height of 1 m, for three different glazing units and for the azimuth angle $\alpha=45^{\circ}$ of the window in dependence on the depth of the room. At (a) an overcast sky on December 20th and (b) a clear sky on June 20th, at 12:00 h [68].

with a moderate climate can use these prismatic glazing units. According to the room depth, the illuminance of the key areas for a vertically oriented window positioning to the southeast is plotted. These windows also have a two glazing units, a double glazing units (DGU) which is solar controlled and/or a prismatic glazing unit for an over cast sky. The illuminance will fall for DGU and the DGU which is solar controlled, as the room depth will typically increase. The illuminance near the window dropped below that of DGU and the DGU which is solar controlled for the prismatic GU. The propensity to give a homogenous illumination in the room can be accepted for the prismatic glazing unit (PGU). According to the room depth, the lightning of the key areas for the vertical windows positioned to the southeast and furnished with a DGU, a solar controlled DGU or a PGU for a clear sky are contrived. The illuminance will decrease for the DGU and solar radiation controlled DGU, when the depth of the room increases in a characteristic fashion but the decrease will be more pronounced. The illuminance in the nearby areas of the window is less for the PGU as compared to the high illuminance for the DGU and the solar radiation controlled DGU, although it is next to the windowpane that the constituent area has been positioned. The prismatic GU will give an enhanced thermal relieve in the adjoining areas of the window in this scenario. The potential to provide an equal room illumination is observable for the prismatic GU (Fig. 20).

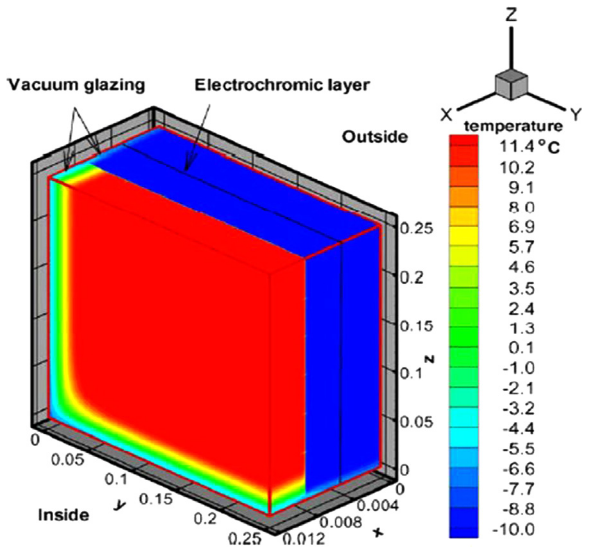

Fig. 21. Predicted isotherms for an EC vacuum glazing with the EC layer facing outside and without incident insolation [72].

The prismatic glazing unit gives enhanced fortification against solar radiations and decreases irradiated hot fluxes during summer and transitional seasons. Glare is not created by the reflecting planes of the prismatic ribs.

A fully functional dynamic prismatic optical element coating was discovered by Shehabi et al. [69] in a study related to solar control, day lighting and energy conservation. He found that the energy usage linked with U.S. commercial electric lighting demand was reduced significantly by 930 TBtu (trillion British thermal units) when the prismatic glazings were combined with conventional vertical daylight strategies. An approximate 85% increase in the energy savings was

Table 13
Effect of glazing properties on window system design and applicable types of dynamic glazing.

Glazing properties	Window system design	Applicable types of dynamic glazing
U-value	• *U*-value of a glazing influences the heat transfer rate from external to internal of the building. • The lower the *U*-value of the glazing, the better the window protection. • The influences of *U*-value in heating load are more than in cooling load. • It is suggested that cold climate region (higher latitudes) should adopt glazing with lower *U*-value to save the heating demand. • For warmer region (lower latitudes), the techno-economics evaluations are able to help in selecting the *U*-value of the glazing. The *U*-value around 1.5 is recommended in cooling dominated regions.	• It is hard to say which dynamic glazing is better in offering us a desired *U*-value as the *U*-value of a glazing depends on its thickness, material and insulation and so on. However, most of the dynamic glazing is outperformed than the static glazing in term of thermal protection, especially glazing such as thermotropic, and aerogel.
Solar heat gain coefficient (SHGC)	• The SHGC of a glazing is an indication for amount of solar heat that penetrates into the building. • Contradiction happens in regions with distinctive summer and winter. In summer, glazing with low SHGC is needed for reducing the solar heat gain in the building. But, in winter glazing with high SHGC is preferable. • It is suggested that heating dominated country should adopt glazing with higher SHGC to reduce heating load. Overheating in summer can be prevented by using shading devices. Besides, dynamic glazing with switchable properties is more suitable in country with distinct seasonal change. • Those regions that are closer to equator (cooling dominated country) are advised to adopt lower SHGC glazing to reduce extra sun heating.	• Electrochromic: Performed well in solar control except in West orientation. • Thermotropic: Performed well in solar control even in West orientation but poor in East orientation. • PV cells: Performed well in solar control (validate in tropical region). • Aerogel: Performances in solar control need more validation. • Phase change material (PCM): Perform well in controlling solar gain especially in summer.
Visible transmittance (Tvis)	• Tvis decides the amount of natural lighting within the building. • Higher Tvis beneficial to daylighting but compromise the thermal energy saving and vice versa. • Optimization of energy saving and daylighting is able to help in determining the Tvis of a glazing. • Window size and window position on wall is equally important to success daylighting in building. Small glazing area is unable to provide sufficient daylight to a building even though the high Tvis glazing is used.	• Electrochromic: Performed well in transmitting daylight except in West orientation. • Thermotropic: Performed well in transmitting diffuse daylight. • PV cells: Performance in daylighting is contradictory with its nature – providing electricity. • Aerogel: Poor in transmitting daylight. • Phase change material (PCM): Performances in visual properties need more validation.

observed in the reduction of electric lighting demand as evaluated from conventional vertical daylight methodologies.

6.4. Vacuum glazing

A transparent thermal insulator used in energy efficient windows is called as vacuum glazing. Two sheets of glass are used with a narrow evacuated space. The principles of Dewar flask have been replicated in the vacuum glazing. Conductive and convective heat flow created by the gas between the two glass plates are reduced by the vacuum, while the radiative thermal transfer is decreased to a lower level by using coatings with low emittance on either one or both of the inner planes of the structures [70]. A heat conductance of less than 0.6 W/m^2 K is obtained by using an all-glass, edge-sealed vacuum window. This was further combined with spherical glass interpane spacers and a coating with low emittance on one internal plane to derive the required thermal conductance [71].

The thermal performance of evacuated glazings was studied by Sullivan et al. [72] to maintain a vacuum between the two panes of glass. The performance of two prototypes of highly insulated super windows and a conventional insulating glass unit was the main foundation for other comparisons. The system was combined with coatings of a low E values and argon gas to compare the performance of these glazings. The solar heat gain coefficient and *U* factor are equally important for highly insulated windows when it comes to heating performances, specifically for West South–East orientations. The performance is significantly affected by the *U*-factor of the window for other orientations, as direct solar radiation is limited in these cases. Lower heating requirements were used in the study for vacuum glazings for most orientations. In case of the Southwest–South–southeast orientation, the performance of the conventional low-E windows was much better than the super windows.

To reduce the peak energy demands for cooling during summer and heating, Fang et al. [73,74] simulated the thermal performance of an EC vacuum glazing using a finite volume model. Three glass panes were used, two of which may have had a low emittance coating separated by a pillar array, and the space formed were evacuated and sealed contiguously using a metal edge seal. The third glass pane with an EC layer was sealed to the evacuated glass unit. When facing the indoor environment, the temperature of the glass pane with the EC layer could reach 129.5 °C for an incident insolation of 600 W m^{-2}. At such temperatures, the occupant comfort would be unacceptable, and the durability of the EC glazing would be compromised. Glass panes with EC layers must therefore face the outdoor environment. In Fig. 21, as insolation increases from 0 W m^{-2} to 300 W m^{-2}, the mean surface temperature of the outdoor glass pane also increases significantly.

7. Lessons learned

Window glazing improved the fenestration system through its optical and thermal properties. Thickness, coating, tinted and spacer between panes are important parameters for determining thermal and daylight aspects of the glazing. Static glazing offered fixed thermal and optical properties while dynamic glazing was considered more advanced due to its switchable thermal and optical properties. Out of all dynamic glazing, electrochromic glazing is the most popular, and its performance was widely investigated by researchers. Thermotropic window may be less popular, due to its visual provision, but its thermal performance had been confirmed by the researchers. PV glazing has been in use due to its ability to provide electricity, thermal and visual comfort.

Table 14
Comparison between static and dynamic glazing at different criteria.

Criteria	Static glazing	Dynamic glazing
Thermal properties	Offer a static thermal property due to the fixed thickness of glazing and glazing material.	Offer a range of thermal properties due to the changeable state of material even though thickness of glazing is fixed.
Optical properties	Allow a fixed amount of optical transmission.	Allow a range of optical transmission.
Window sizing	Offer limited choice of window size for the balance between energy saving and daylighting. Designers have to decide which feature is more critical for the building.	Offer wide range of choices in window sizing. It allows designers to adopt large glazing area with minimum side effect in thermal performance.
Window orientation	Need serious consideration in term of window orientation especially to secure thermal performance. Static glazing is not recommended to install in East and West orientations; adopt shading devices if those orientations are unavoidable	Offer more flexible options in term of window orientation. However, a West window intercepts high level of direct sunlight. Hence, it needs serious consideration of the shading devices even if dynamic glazing is used
Region of employment	Due to the static thermal and optical properties, static glazing is more suitable to be employed by the region that does not have distinctive seasonal climate change.	In seasonal countries, the requirements for window performances are contradict in summer and in winter. Thus, switchable dynamic glazing offers more options in window protections
Costs	The qualities and performances of glazing are proportional to the costs. It is wise to perform techno-economics evaluation to obtain the suitable glazing for a building. Generally, due to the higher costs of dynamic glazing, it is more suitable to be installed in the building which needed high performances in term of daylighting and energy saving such as commercial building.	
Optimization	Both static and dynamic glazing have their own contradictions in offering a balance between daylighting and energy saving. Therefore, optimization is important for both glazing. However, compared to dynamic glazing, designing a static window usually needed more substantial consideration of optimization in term of energy and daylight performances especially for commercial building.	

The variety of glazing in the market provides more choices to building designer. But, this is also making their task in designing window become more challenging as selecting a glazing is crucial for visual and energy aspects of the building. Moreover, all the glazing may be contradictory in certain features; therefore, optimization process is needed. Optimization process involves sacrifices on some aspects to open opportunity for other aspects. Besides, it also aimed to provide the ideal balance among the considered features while minimizing the contradiction between them. For instance, the triple pane window would definitely outperformed double panes, due to its thickness that increases the *U*-value, but from a financial point of view, it might not be optimum, and similar to EC glazing; it will reach an optimum stage by providing daylight and thermal comfort, below or surpassing the optimum stage, yielding undesired outcomes. PV glazing optimization occurred in terms of electricity generation and daylight penetration.

Using an internal vacuum between two glass sheets to eliminate heat transport by gas conduction and convection greatly reduces the heating energy demand of buildings by minimizing the thermal transmittance of glazing. Vacuum glazings have lower heating requirements than superwindows for most window orientations. The conventional low-E window outperforms the superwindows for Southwest–South–Southeast orientations. The prismatic glazing unit can be used for common windows to bring daylight deep into a space and to control the distribution of direct sunlight. The prismatic glazing unit also provides improved protection against solar irradiation and distinctly reduced irradiated heat fluxes. Moreover, the reflecting surfaces of the prismatic ribs do not create glare.

Beyond of the properties of the glazing itself, climate background is also a very important key to determine the suitable glazing for the building. Climate background is heavily dependent to the locations of the site. Therefore, we are able to generalise some glazing properties with locations of the buildings (Table 14).

Two relatively new technologies – aerogel and phase change material (PCM) were reviewed as well. These technologies were expected to provide more choices in glazing options. However, aerogel and PCM glazing needed more scientific verification in order to provide a holistic reference to a building designer. Furthermore, the drawbacks of aerogel and PCM might still be mitigated; which requires innovation of scientists and continuous R&D. However, the most important aspects and lessons learned from this study are summarized in Tables 13 and 14.

8. Conclusion

Selecting a glazing for window system is still crucial where both static and dynamic glazing have their own contradictions in offering a balance between visual and energy aspects. Beyond of the glazing properties itself, contradiction happens in regions with distinctive seasonal change. Therefore, climate background is also a very important key to determine the suitable glazing of buildings. Optimization process is important for both glazing types; it involves sacrifices on some aspects to open opportunity for other aspects in order to provide the ideal balance among the considered features while minimizing the contradiction. However, compared to dynamic glazing, designing a static glazing window usually needs more substantial consideration of optimization. Generally, the qualities and performances of glazing are proportional to the costs. It is wise to perform techno-economics evaluation to obtain the suitable glazing for a building. Due to the higher costs of dynamic glazing, it is more suitable to be installed in the building which needed high performance in term of daylighting and energy saving such as commercial buildings.

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